Draft Chapter 4
WHY STORMWATER MATTERS

4.0 INTRODUCTION

When a city takes a bath, what happens to the dirty water?

Stormwater runoff is overland flow from precipitation that accumulates in and flows through natural or man-made conveyance systems during and immediately after a rainfall vent or upon snowmelt. Average annual rainfall varies across most of Virginia from about 42-48 inches per year, with averages in isolated areas of less than 38 inches or more than 66 inches **(Figure 4.1)**. Virginia has a number of major rivers that flow from the mountains through the state to the coast. Many areas of Virginia have the type of geology that allows water to infiltrate to underground aquifers. These aquifers provide a significant amount of drinking water to Virginia citizens.

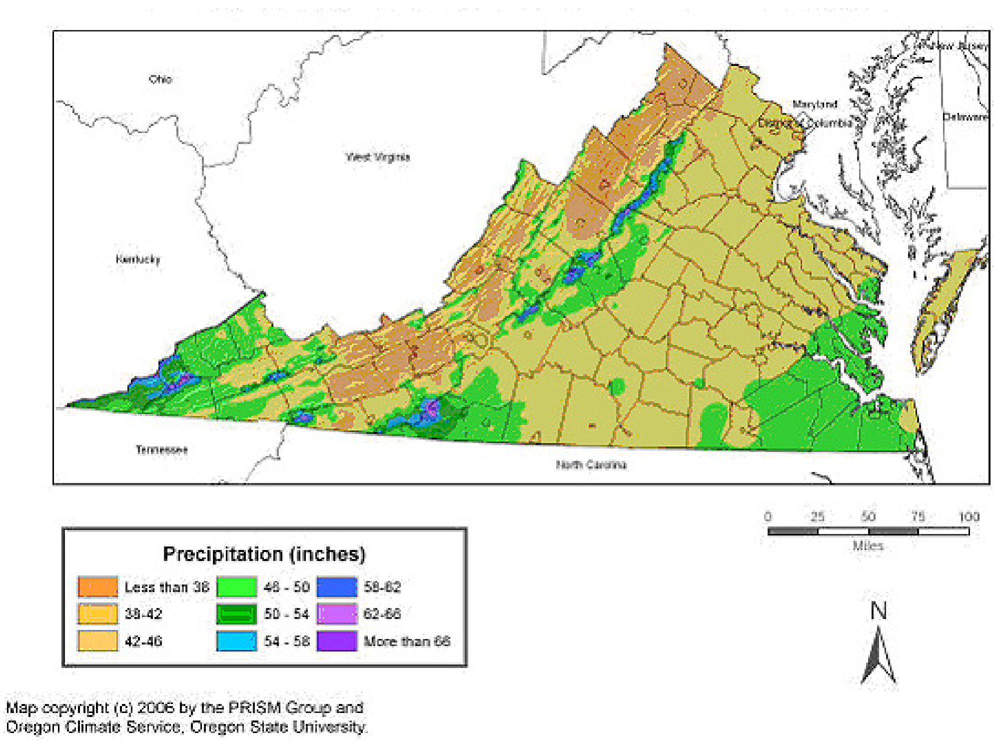


Figure 4.1: Average Virginia Annual Precipitation, 1971-2000
Source: Oregon Climate Service

Stormwater runoff has traditionally been viewed as a nuisance to be disposed of as quickly as possible. However, we must learn to ~~see~~ view stormwater as a valuable resource and manage it more carefully than we have in the past. There are two key reasons for this: (1) there is only a fraction of the earth's total water available as fresh water; and (2) the availability of fresh water is critical for human health and survival. To really grasp the value of stormwater management, we first need to understand how water circulates throughout our world.

4.1 THE HYDROLOGIC CYCLE

It is one of nature's wonders that we never run out of water. After four and a half million years we continue to have water available for our use because of a natural process called the hydrologic cycle. The sun provides the energy that powers this remarkable process. Our water is constantly being exchanged between the earth and the atmosphere (**Figure 4.2**) in a natural form of recycling. The sun's energy, in the form of light and heat, evaporates water from oceans, rivers, lakes and even puddles. Water is also transpired by plants and animals and evaporated from the soil. In combination, these processes are know as evapotranspiration.

Rising air currents lift the water vapor up into the atmosphere. When the water vapor reaches the cooler layers of the atmosphere, it condenses to form clouds. As clouds grow larger and move around, eventually the water droplets grow larger and heavier, falling to the earth's surface as precipitation (rain, snow, sleet or hail). Very little of our local rainfall is due to local evaporation and transpiration. Our rain is moisture that has been transported [j.m.] by clouds from elsewhere.

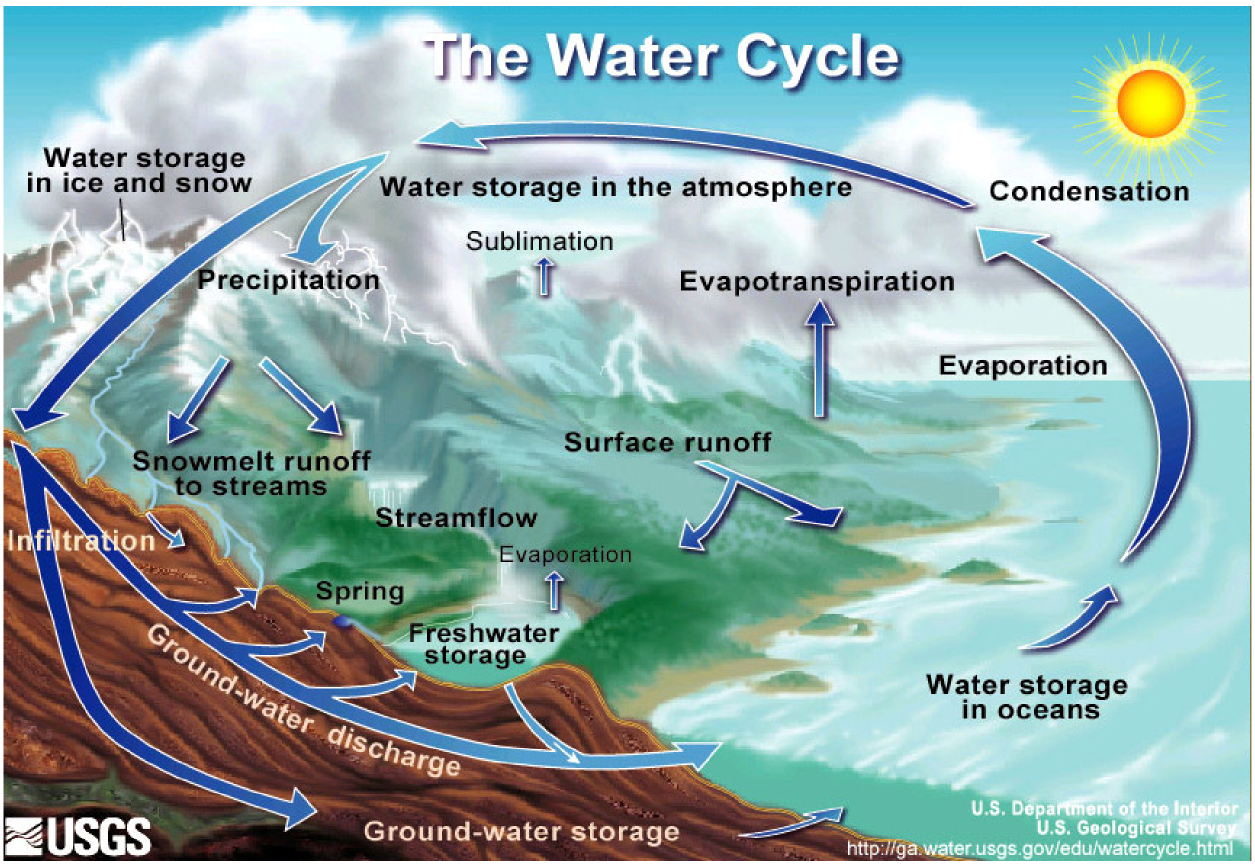


Figure 4.2. The Hydrologic Cycle *(USGS web site)*

Once the precipitation reaches the ground, several things can happen to it. The water may evaporate, be absorbed by the ground and taken up by plant roots, or it may infiltrate the soil and become groundwater, one of the world's largest storehouses of water. The rest becomes *surface runoff* or ***stormwater runoff*** that drains into streams, rivers, and other surface waters. This representation, while depicting the general concept, over-simplifies this complex process and does not include the impact of man's actions on the hydrologic cycle.

4.2 DISTRIBUTION OF THE EARTH'S WATER – THE WATER BUDGET

Water covers approximately 70% of the earth's surface, but we only see a small portion of it. Many people do not understand that most of the earth's water is *not* available for man's use (**Figure 4-3**). Almost 94% of the planet's water is chemically bound up in the rocks and minerals of the earth's crust. The oceans comprise about 97% of the available water, but ocean water is not significantly useable for human consumption due to its salt content.

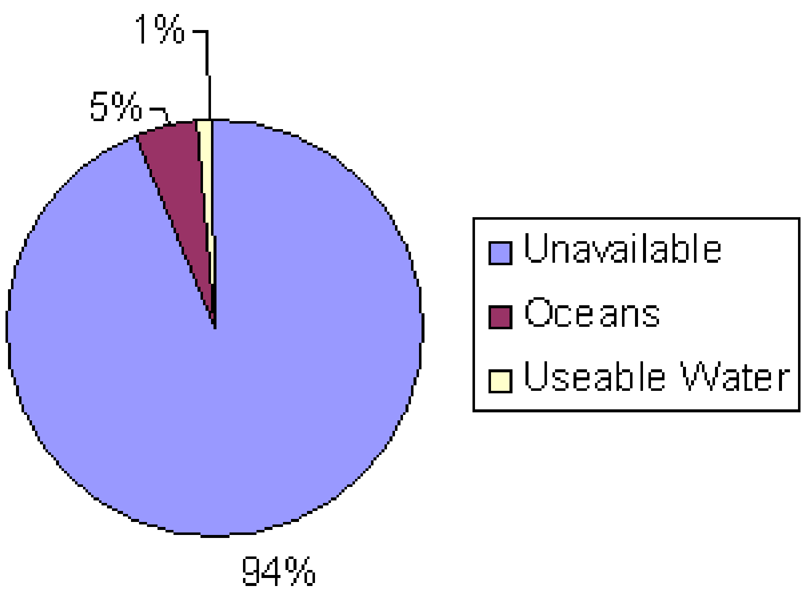


Figure 4.3. Overall Water Budget
Source: Day and Crafton, 1978

We may consider the remaining water – about 1% of all the earth's water, or 3% of the available water – to be useable for our basic needs (**Figure 4.4**). Of this useable water, almost 93% is stored in aquifers, and nearly 7% is found in polar glacial ice masses. The remainder – about one eighth of one percent (0.125 %) – is composed of circulating ground water, inland waterways, and atmospheric moisture.

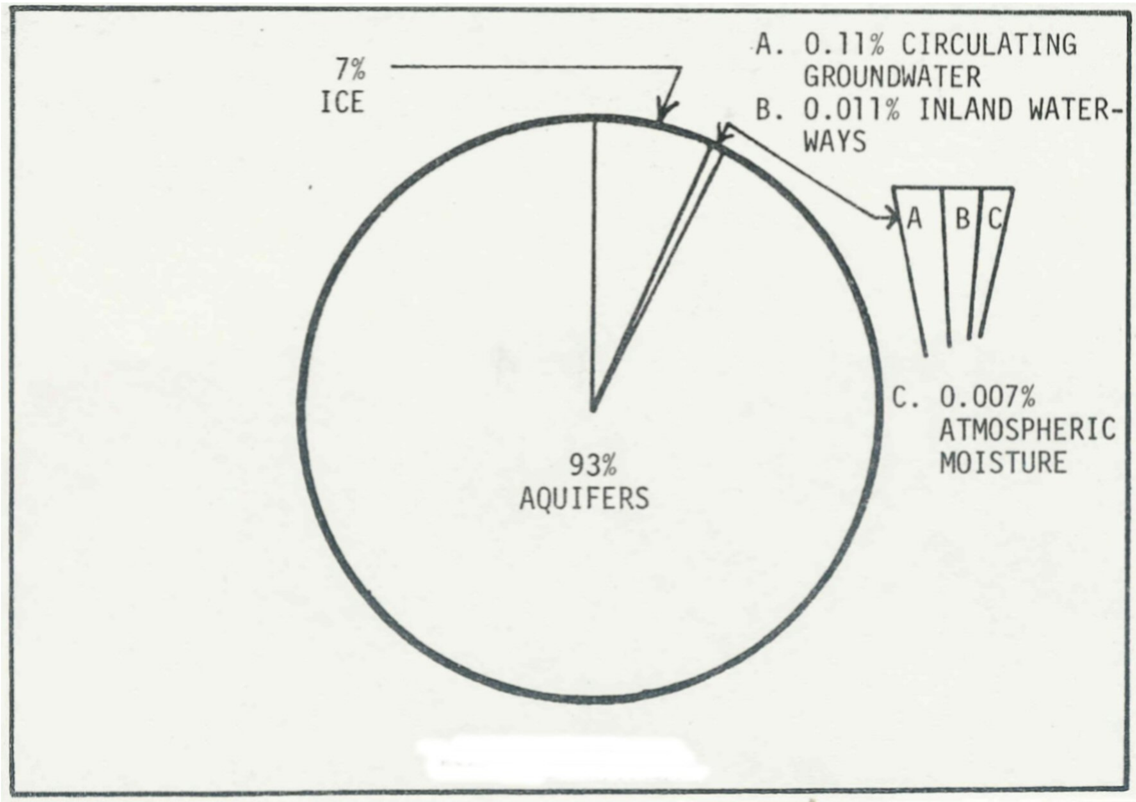


Figure 4.4. Available Water Budget *(Source: Day and Crafton, 1978)*

There is about ten times as much water circulating in the ground as there is on the earth's surface in lakes, rivers, streams and glaciers and about twice as much surface water as there is moisture in the atmosphere. It is important to understand that *all* of the available water has been, for many years, subject to pollution from man's activities.

Smokestacks spew air pollutants into the atmosphere, which become bound up in the water particles in clouds and subsequently drop to the earth as rain. Pipes from industrial and sewage treatment plants and stormwater conveyance systems carry pollution into our streams and rivers. Water that filters into the soil can carry pollutants into the groundwater tables that provide base flow for our streams, or even into deep aquifers. Given the reality that the water we see *and* use each day is a small part of the total, we need to treat stormwater as a valuable resource and not view it as disposable.

4.3 THE IMPACT OF CLIMATE CHANGE

We are all aware of the ongoing debate regarding global warming and related climate changes. The most thorough evaluation of the global warming phenomenon, including predictions of potential future results, comes from the Intergovernmental Panel on Climate Change (IPCC), which revised its outlook in early 2007 (2007a, 2007b). The Union of Concerned Scientists and the Ecological Society of America (2005) and other climate researchers, have affirmed global warming and provided predictions of what might happen as a result.

It is important to understand that global warming is not just temperature change. There are secondary effects that result from the temperature change. **Table 4.1** summarizes the most recent IPCC update, plus additional input from the Union of Concerned Scientists and the Ecological Society of America series on regional climate impacts.

Table 4.1. Summary of Climate Changes* Leading to Stormwater Impacts

Changing Feature	Primary Impact	Secondary Impact
Precipitation	More mixed winter precipitation; more ice and/or rain-on-snow events	More runoff during winter; increased road salt usage because of more ice
	Less rain during summer season	Drier surface-water bodies for longer periods; increased water-level fluctuations; wetland and floodplain disconnection
	Longer, more severe droughts over larger areas	Soil moisture depletion; more accumulated surface pollution; less available water supply
	More extreme precipitation events	Flooding; erosion; rapid water-level changes
Warmer winters	Less snow accumulation; more and earlier winter runoff; earlier snowmelt	Less water supply saved in snowpack (especially in the west); more winter road salt application; drier streams, wetlands, and floodplains earlier in the year; less groundwater recharge
	Shorter lake ice coverage	Earlier lake turnover in spring, later in fall; greater algal growth; more evaporation during winter; longer lake water stratification period
Warmer summers	Increased temperature of runoff	Less cold-water fishery
	Increased humidity	Greater severity of storms and extreme events like tornadoes
	More suitable vector environment	Increases in the number and type of nuisance and health-related vectors (like mosquitoes in stormwater ponds)
	Less water available in wetlands, lakes, reservoirs, and streams	Evapotranspiration-transpiration increases result in volume loss; groundwater recharge decreases, affecting stream base flow
	Gradual warming of the oceans	Increased tropical storm frequency and severity; sea level rise
	Lower water levels	Some perennial streams become intermittent; hydrologic connections to riparian zone decrease
* Variations will occur in different parts of North America		

Source: Adapted in part form IPCC 2007a, IPCC 2007b, and UCS-ESA 2005

The increase in global warmth drives precipitation patterns. In most parts of the United States we are seeing an increase in winter and spring precipitation and a decrease in summer and fall precipitation. The rate of evaporation increases as land and surface water temperatures increase and, as air temperature increases the air can hold more moisture. Thus, scientists expect global warming to increase the frequency and intensity of precipitation. It is important to understand that increased frequency and intensity of precipitation does not necessarily translate into more total rainfall, just more concentration of moisture when precipitation does occur.

Scientists at the National Climatic Data Center (NCDC) have concluded that most of the observed increase in storms with heavy and very heavy precipitation has occurred in the last three decades. These storm events may vary in character from high-intensity rainfall cells accompanying weather fronts to tropical storms that inundate coastal areas before moving inland to continue dumping large volumes of rain or snow. The consequence of more frequent and intense storms may include flooding, erosion, pollution of waterways with excess runoff, crop damage, and other environmental and economic damage.

Virginia has seen a 25 percent increase in the frequency of extreme precipitation events since 1948. This is the greatest such increase among all states in the South Atlantic region (Maryland to Florida). An increase in the number of downpours does not necessarily mean more water will be available. The intensity and duration of droughts is increasing in Virginia. This means that soil moisture will be depleted, annual groundwater recharge will decrease, and runoff from hardened dry soil surfaces could increase.

If less water infiltrates into the ground and and runoff increases, more frequent and severe flooding is possible. During the 20th century, floods have caused more property damage and loss of life in the United States than any other type of natural disaster. The reciprocal impact of more water running off is less infiltration. This translates during the year into decreased stream base flow, since less water is stored in the shallow groundwater zone. Less infiltration will also mean less groundwater supply.

The combination of extreme events and droughts means that water level fluctuations will be commonplace as storage areas (ponds, wetlands, floodplains) change very quickly from dry, exposed conditions (e.g., Lake Chesdin in the summer of 2007) to flooded, high-water conditions that typically follow large storm events.

Increasing population in Virginia and elsewhere is placing continual pressure on our water supplies. Competition for water will also increase as drier conditions translate into increased irrigation demand for crops and lawns. Stormwater managers will be on the front lines in trying to cope with these changes and continue to maintain the quality of life the public has come to expect.

4.4 THE AVAILABILITY OF WATER FOR HUMAN USE AND RAINWATER HARVESTING

Since water is a finite resource, current and future plans must strive to maintain or improve the quality of available water while utilizing the available water resources as efficiently as possible. This is becoming even more important as populations increase. A recent report by Credit Suisse

(Garthwaite, 2007) indicates 18 countries will experience water demand beyond supply capabilities by 2025.

Worldwide water consumption is rising at double the rate of population growth (Garthwaite, 2007). Similarly, Virginia's water consumption is continually increasing. In 2005, 59% of the state's water was used for public consumption with 36% coming from groundwater sources (Virginia DEQ, 2006). These numbers are up from 2004 and 2003, where 57% and 54% of water was for public consumption, ~~with~~ and 33% and 12% coming from groundwater, respectively (Virginia DEQ, 2004 and 2005).

Due to the increasing demand for public water supplies, groundwater levels are declining and municipal treatment plants are struggling to supply current demands while dealing with declining infrastructures. Unfortunately, we have continued to treat runoff as a waste product, moving it off developed land as fast as possible. Instead, as stormwater managers, we should be treating stormwater as a valuable resource.

Virginia's growing population places increasing demands on water supplies. As a result, planners, county and state officials, residents, and developers must look at alternative water sources to supply the demands. Rainwater harvesting offers an affordable, simple, sustainable and reliable alternative water source. Not only does rainwater harvesting supply water for indoor and outdoor use, it protects the environment from detrimental nonpoint source pollution by reducing rooftop runoff.

Rainwater harvesting is ideal for large retail and industrial buildings (**Figure 4.5**). Rainwater can be diverted from the flat roof to either an on-site storage tank(s) or pond. Stored water is then diverted both indoors and outdoors to be recycled for toilet flushing, linen washing, facility cleaning, fire suppression, cooling towers, industrial processes, and landscape irrigation. Not only does the company save on water consumption costs, but it also reduces the amount of stormwater runoff that must be treated prior to leaving the site.

Figure 4.5. Rainwater Harvesting Tanks – Large Scale Use

Rainwater harvesting can also be cost-effective for homeowners (**Figure 4.6**). Rainwater is typically cleaner than the municipal water supply, and the water is typically softer. Soft water requires less laundry detergent than hard water. Use of free rainwater to flush toilets, do laundry, fill swimming pools, wash vehicles and power-wash the home, and irrigate lawns is much more sensible and cost-effective than paying for municipally treated water to accomplish those same functions. Furthermore, as a growing population places more demands on municipally treated water, the cost of that water supply will rise. Therefore, the economics of rainwater harvesting will pay greater dividends in the future.

Figure 4.6. Rainwater Harvesting Tank – Residential Scale

More and more states and municipalities, including Virginia, are now requiring that stormwater runoff be reduced in new developments through the use of low impact development practices. Rainwater harvesting is a sustainable approach for accomplishing this, while providing an alternative water source at the same time. Acting proactively to protect the environment and conserve resources is beneficial both today and tomorrow.

The Cabell Brand Center in Salem, Virginia, has produced the *Virginia Rainwater Harvesting Manual 2007*, which details the benefits of rainwater harvesting, both economical and environmental, and provides best management practices for rainwater harvesting design and utilization.

4.5 HOW POPULATION GROWTH AND LAND DEVELOPMENT AFFECT THE HYDROLOGIC CYCLE

Point and nonpoint source water pollution from pipes, streets, rooftops, and parking lots swell downstream waterways every time it rains. Since the natural vegetation and soils that could absorb it have been paved over, stormwater becomes a high-speed, high-volume conduit for pollution into streams, rivers, lakes and coastal waters.

Most Virginia cities have separate stormwater sewer systems through which stormwater discharges directly into waterways. These storm flows often cause streambank erosion and carry pollutants directly into waterways. In older cities, such as Richmond and Lynchburg, stormwater flows into the same pipes as sewage, which sometimes results in combined combined sewer overflows (CSOs), dumping untreated human, commercial, and industrial waste into waterways.

Contaminated stormwater from CSOs are required to be controlled under the Clean Water Act and Virginia laws and regulations. However, progress is slow because the problems are large and multi-faceted, and the solutions are often expensive.

For the past three decades the population in the Chesapeake Bay Watershed has grown by more than a million people per decade. This trend is projected to continue at least for the next 40 years. Between 1990 and 2000, the watershed population increased by 8% while the impervious cover increased by an unsustainable 41% (USEPA, 2007). During this same time, forest cover decreased substantially in most areas of the watershed.

State estimates predict that by 2030 there will be over three million additional people living within the Bay watershed (USEPA, 2007). This dramatic increase in population, impervious cover, and corresponding loss of tree cover in the watershed has resulted in excess amounts of stormwater runoff. With the loss of natural vegetation, there is an increasing amount of pollution and something called the "urban stream syndrome." Urban steam syndrome is characterized by flash flooding, elevated nutrient and contaminant levels, altered stream morphology, sedimentation from eroded stream banks and loss of biological diversity (Mehan, 2008). Water quality and quantity are intertwined as never before. The increased and degraded runoff is destroying local streams, causing damage to infrastructure and properties and risking our water supply sources.

The USEPA has ranked stormwater runoff as the second most prevalent source of water quality impairment in the nation's estuaries (agriculture is currently ranked as number one). However, with the large projected increase in population expected in Virginia, urban stormwater issues will likely become much more significant in the near future and could rival agriculture as the number one impact to water quality.

Changes to the land surface, along with inappropriate stormwater management, can significantly alter the hydrologic cycle. In a natural Virginia woodland or meadow, very little of the annual rainfall leaves the site as runoff. Little runoff will occur from most wooded sites until over an inch of rain has fallen.

Remember that in the hydrologic cycle, more than half of the annual amount of rainfall returns to the atmosphere through evapotranspiration. Surface vegetation, especially trees, transpires water to the atmosphere (with seasonal variations). Water is also stored in puddles, ponds and lakes on the earth's surface, where some of it will evaporate. Water that percolates through the soil either moves vertically or laterally (**Figure 4.7**). The vertical flow eventually reaches the zone of saturation (water table or aquifer) and is stored in the soil. The lateral flow through the soil often emerges as springs or seeps, providing base flow for streams.

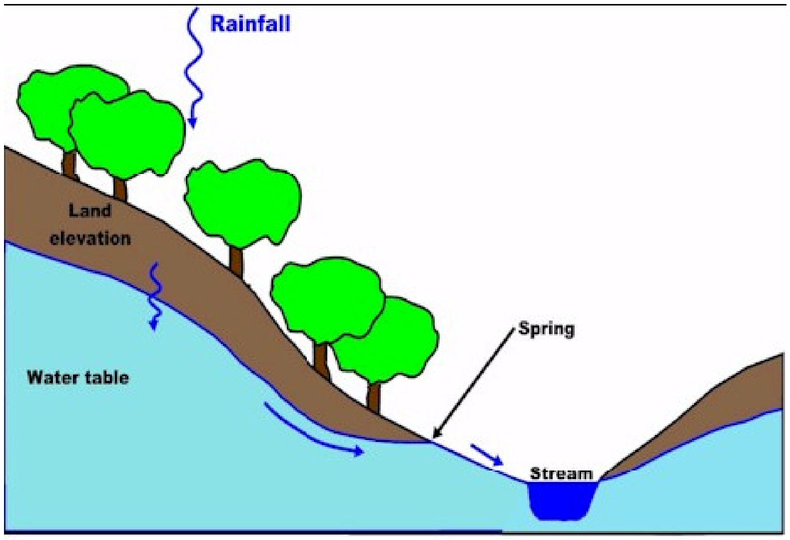


Figure 4.7. Relationship of infiltration to groundwater storage and stream base flow (PA DEP, 2006)

Soils are influenced and formed by vegetation, climate, parent geologic material, topography and time. All of these factors have some effect on how water will move through the soil. Restrictive soil horizons may impede the vertical movement of water and cause it to move laterally. It is important to understand these factors when designing an appropriate stormwater system at a particular location. Although the total amount of rainfall varies somewhat in different regions of the state, the basic average hydrologic cycle shown in **Figure 4.8** holds true. Under natural woodland and meadow conditions, only a small portion of the annual rainfall becomes stormwater runoff.

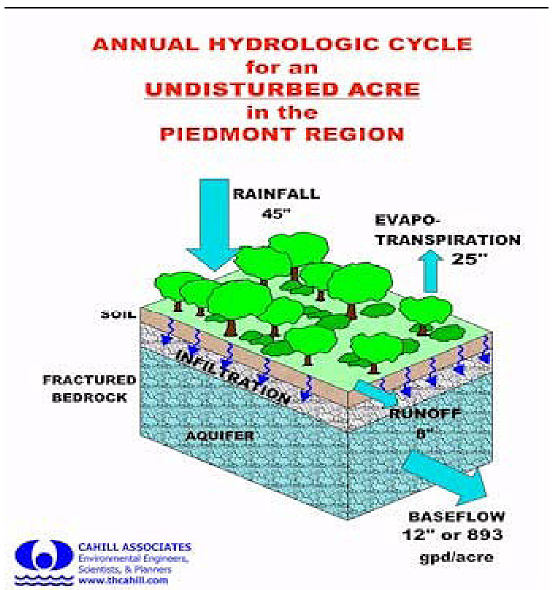


Figure 4.8. Hydrologic Cycle on Undisturbed Land (PA DEP, 2006)

Changing the land surface causes varying changes to the hydrologic cycle (**Figure 4.9**). Altering one component of the water cycle invariably causes changes in other elements of the cycle. Roads, buildings, parking areas and other impervious surfaces prevent rainfall from infiltrating into the soil and significantly increase the amount of runoff. As natural vegetation is replaced with impervious surfaces, natural drainage patterns are altered; the amount of evapotranspiration and infiltration decreases and runoff increases.

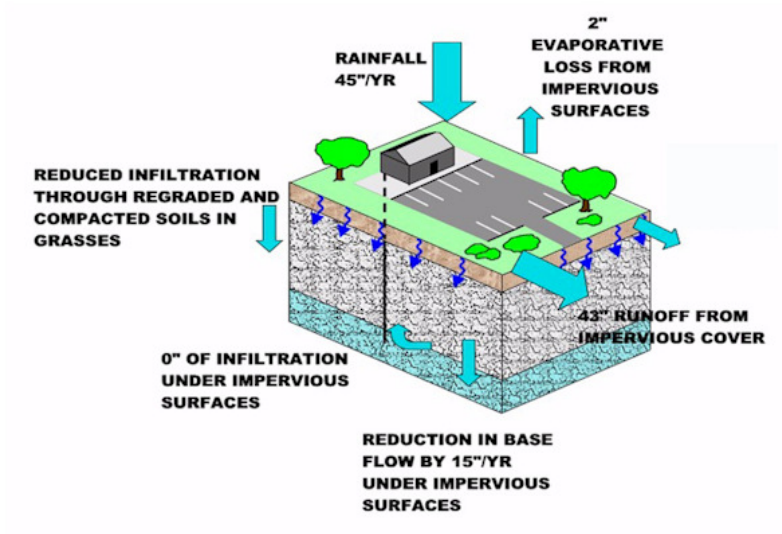


Figure 4.9. Hydrologic Cycle on Developed Land (*PA DEP, 2006)*

These changes in the hydrologic cycle have a dramatic effect on streams and water resources. Annual stormwater runoff volumes increase from inches to feet per acre, groundwater recharge decreases, stream channels erode, and populations of fish and other aquatic species decline.

In addition, natural pollutant removal mechanisms provided by on-site vegetation and soils have less opportunity to remove pollutants from stormwater runoff in developed areas. During construction, bare soils are exposed to rainfall, which increases the potential for erosion and sedimentation. Development can also introduce new sources of pollutants from everyday activities associated with residential, commercial, and industrial land uses. The development process is known as *urbanization*. Stormwater runoff from developed areas is commonly referred to as *urban stormwater runoff* or *urban runoff*.

4.5.1 Specific Environmental Impacts of Land Development on Stormwater

Urban stormwater runoff can be considered both a point source and a nonpoint source of pollution. Stormwater runoff that flows into a conveyance system and is discharged through a pipe, ditch, channel, or other structure is considered a point source discharge. Stormwater runoff that flows over the land surface and is not concentrated in a defined channel is considered nonpoint source pollution. In most cases stormwater runoff begins as a nonpoint source and becomes a point source discharge. Both point and nonpoint sources of urban stormwater runoff have been shown to be significant causes of water quality impairment to rivers and streams. Urban runoff is also reported as a contributor to excessive nutrient enrichment in numerous lakes and ponds throughout the state, as well as a continued threat to estuarine waters and the Chesapeake Bay.

Impervious cover has emerged as a measurable, integrating concept used to describe the overall health of a watershed. Research has established ecological stress thresholds, which show that when impervious cover in a watershed reaches between 10 and 25 percent, ecological stress becomes apparent. Beyond 25 percent, stream stability is reduced, habitat is lost, water quality becomes degraded, and biological diversity decreases.

To put these thresholds into perspective, typical total imperviousness in medium density, single-family home residential areas range from 20 to nearly 60 percent. **Table 4.2** indicates typical percentages of impervious cover for various land uses in the Northeast United States. It is important to note that these tabulated values reflect impervious coverage within individual land uses, but do not reflect overall watershed imperviousness, to which the ecological stress thresholds apply. However, in developed watersheds with significant residential, commercial, and industrial development, overall watershed imperviousness often exceeds the ecological stress thresholds.

The impacts of development on stream ecology can be grouped into four categories:

1. Hydrologic Impacts
2. Stream Channel and Floodplain Impacts
3. Water Quality Impacts
4. Habitat and Ecological Impacts

The extent of these impacts is a function of climate, level of imperviousness, and change in land use in a watershed.

Table 4.2. Typical Impervious Coverage of Land Uses in the Northeast U.S.

Land Use	% Impervious Cover
Commercial and Business District	65-100
Industrial	70-80
High Density Residential	45-60
Medium Density Residential	35-45
Low Density Residential	20-40
Open (Natural Areas)	0-10

Source: MADEP, 1997; Kauffman and Brant, 2000; Arnold and Gibbons, 1996; Natural Resource Conservation Service, 1975

4.5.1.1 Hydrologic Impacts

The impacts of development on hydrologic regime of a site or watershed, as a result of increases in impervious surfaces, may include:

- Loss of vegetation, resulting in decreased evapotranspiration
- Soil compaction
- Reduced groundwater recharge
- Reduced stream base flow
- Increased runoff volume
- Increased peak discharges
- Decreased runoff travel time
- Increased frequency and duration of high stream flow
- Increased flow velocity during storms
- Increased frequency of bank-full and over-bank floods

Loss of Vegetation. On woodland and meadow areas, over half of the average annual rainfall returns to the atmosphere through evapotranspiration. The vegetation itself also intercepts and slows the rainfall, reducing its erosive energy, reducing overland flow of runoff, and allowing infiltration to occur. The root systems of plants also provide pathways for downward water movement into the soil mantle.

Evapotranspiration varies tremendously with season and with type of vegetative cover. Trees can effectively transpire most of the precipitation that falls in summer rain showers. Evapotranspiration dramatically declines during the winter season, since temperatures are lower and vegetation is dormant. During these periods, more precipitation infiltrates and moves through the root zone, and the groundwater level rises. Removing vegetation or changing the land type from woods and meadow to residential lawnscapes reduces evapotranspiration, reduces infiltration and increases the amount of stormwater runoff.

Soil Compaction. Soil disturbance and compaction also increase stormwater runoff. Soils contain many small openings called "macropores" that allow water to move through the soil, especially under saturated conditions. Soil *permeability* is the property of soil or rock to pass water through its mass and is dependent on both the volume of pores and openings (*porosity*) as well as on how these pores are connected to one another. When soil is disturbed (grading, stockpiling, heavy equipment traffic, etc.) the soil is compacted, macropores are smashed and the natural soil structure is altered. Soil permeability characteristics are substantially reduced.

Compaction can be measured by determining the bulk density of the soil. The more compacted the soil is, the heavier it is by volume. Heavy construction equipment can compact soil so significantly that the bulk density of lawn soil approaches the bulk density of concrete (**Table 4.3**). The result is a surface that is functionally impervious because the water absorbing capacity of the soil altered so much.

Table 4.3. Common Bulk Density Measurements

Land Surface/Use	Bulk Density
Undisturbed Lands Forest & Woodlands	1.03 g/cc
Residential Neighborhoods	1.69 to 1.97 g/cc
Golf Courses - Parks Athletic Fields	1.69 to 1.97 g/cc
Concrete	2.2 g/cc

Reduced Groundwater Recharge and Reduced Stream Base Flow. When stormwater runoff during a storm event is allowed to drain away rather than recharge the groundwater, it alters the hydrologic balance of the watershed. As a consequence, stream base flow is deprived of constant groundwater discharge, and the flow may diminish or even cease. During a drought, reduced stream base flow may also significantly affect the water quality in a stream. As the amount of water in the stream decreases, the oxygen content of the water often falls, affecting the fish and macroinvertebrates that live there. A reduction in oxygen content can also create chemical reactions that release pollutants previously bound up in bottom sediments.

Soils form over time in response to their landscape position, climate, presence of organisms and parent material. Soils that have formed in place from the weathering of their parent material usually form a typical profile with A, B and C horizons (layers) above bedrock. However, many soils form from a combination of the weathering of parent materials and the deposition of transported soils creating a more complex layering effect. In general, any interface between soil layers can slow the downward movements of water through a soil profile and promote lateral flow. This is especially true in sloping landscapes typical of the Piedmont and Ridge-Valley provinces of Virginia.

Water moves through the soil until it is lost through evapotranspiration or reaches the groundwater table and replenishes the aquifer. The movement of water through the soil is influenced by a soil's texture, structure, layering and the presence of preferential flow pathways (macropores). Soil textures are defined by the percentage of sand, silt and clay present in the soil. In general, the permeability and hydraulic conductivity of a soil will decrease with decreasing soil particle size (i.e., water moves more easily through sands, which have larger particles and pore spaces, than silts and clays in which the soil particles and pore spaces are respectively smaller). **Table 4.4** shows regional estimates of the average annual groundwater recharge volume based on soil type.

Table 4.4. USDA-NRCS Estimates of Annual Groundwater Recharge Rates, Based on Soil Type

Hydrologic Soil Group (HSG)	Recharge Rate
Hydrologic Soil Group A	18 inches/year
Hydrologic Soil Group B	12 inches/year
Hydrologic Soil Group C	6 inches/year
Hydrologic Soil Group D	3 inches/year
NOTE: Average annual rainfall varies from approximately 42 - 48 inches across Virginia	

There is often a discontinuity of soil-water movement at the interface between soils of different textures or structures or in the presence of restrictive soil layers, including clay lenses, fragipans (commonly found in colluvial and glacial soils), and plow pans (compressed layers of soil formed by the repeated traversing by moldboard plows on farmland). This layering causes percolating water to concentrate at certain points along the layer interface. This disruption often causes water to "back up" at the interface, which can cause water to move laterally through the soil.

Soil water also follows preferential flow paths through the soil. Preferential flow paths include pathways created by plant roots, worm or rodent burrows, cracks or voids in the soil resulting from piping action caused by the lateral movement of soil-water. Preferential flow paths also form at the soil rock interface and within rock structures.

A variety of processes can occur when precipitation falls on a natural soil surface. Hill slope hydrology processes have been identified by Chorley (1978) and are systematically illustrated in **Figure 4.10**. The flow processes illustrated here are only representative examples of the complex interactions that occur in nature. Simplified descriptions of these processes follow the graphic.

Most of these flow processes occur naturally within Virginia watersheds (p.h.). The extent to which one or more of these processes are active within a particular area is influenced by soil characteristics, geology and topography or landscape position.

Eventually the groundwater table intersects the land surface and forms springs, first order streams and wetlands (**Figure 4.7 above**). This groundwater discharge becomes stream base flow and occurs continuously, during both wet and dry periods. Much of the time, all of the natural flow in a stream is from groundwater discharge. In this sense, groundwater discharge can be seen as the "life" of streams, supporting all water-dependent uses and aquatic habitat. First-order streams are defined as "that stream where the smallest continuous surface flow occurs" (Horton, 1945), and are the beginning of the aquatic food chain (**Figure 4.11**) that evolves and progresses downstream. **As the link between groundwater and surface water, headwaters represent the critical intersection between terrestrial and aquatic ecosystems.** During periods of wet weather, the water table may rise to near the ground surface in the vicinity of the stream. This higher ground water table coupled with through-flow, return-flow and shallow subsurface flow result in an area of saturation in the vicinity of the stream channel.

Figure 4.10. Components of hill slope hydrology (Adapted from Chorley, 1978)

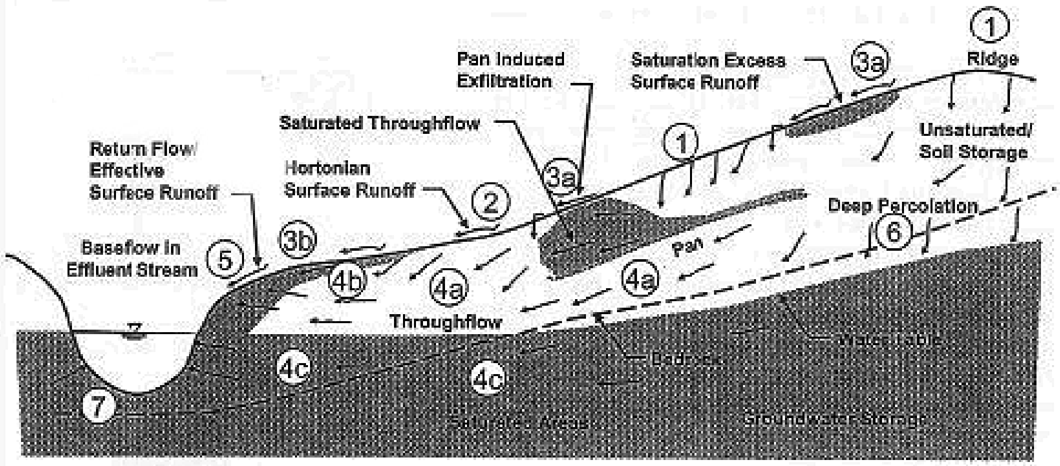


Figure 2. Components of hillslope hydrology (Adapted from Chorley [1978])

1. Areas marked with a “1” are areas where the infiltration capacity of the soils exceeds the rainfall rate. All rain falling on these areas infiltrates into the ground.
2. Areas labeled with a “2” identify an area where the rainfall rate exceeds the surface infiltration rate, and the excess rainfall becomes surface runoff (Hortonian surface runoff).
3. Areas marked with a “3” represent areas where the soil has become saturated and cannot hold additional moisture; all rain falling on these areas immediately becomes surface runoff. Saturation can occur as a result of various subsurface conditions. Areas marked “3a” illustrates where a restricting layer (fragipans, clay lenses, etc.) limits the downward movement of soil water creating a perched water table that reaches the ground surface. Area “3b” identifies an area where water moving through the soil (through-flow) reaches the surface as a spring or seep (return-flow); in these cases the surface in the vicinity of the seep or spring becomes saturated.
4. Areas marked with a “4” represent areas of through-flow. Through-flow is the lateral movement of water through the soil. Area “4a” illustrates through-flow along preferential flow paths in unsaturated soils; area “4b” shows shallow surface flow (a common occurrence in PA); and area “4c” illustrates through-flow in saturated areas.
5. Areas marked with a “5” represent an area of return-flow. Return-flow is water that has moved through unsaturated or saturated subsurface areas and re-appears as surface flow through springs or seeps.
6. The area labeled as “6” represents an area of deep percolation or groundwater recharge.
7. Area “7” points to a location where groundwater discharges to the stream (influent streams). For effluent streams, water moves from the stream into the ground water table in these areas. In some streams, both processes may occur during different times of the year. (Brown/Fennessey/Petersen)

Figure 4.11. Leaves and organic matter are initially broken down by bacteria and processed into food for higher organisms downstream.

As a result, this area saturates quickly during rain events; and the larger the rain event, the more extensive the area of saturation may be. It is understood by researchers that a significant amount of the surface runoff observed in streams during precipitation events is generated from the saturated areas surrounding streams (Chorley, 1978; Hewlett and Hibbert, 1967). The runoff generated from rainfall on saturated land areas is referred to as saturation overland flow. Hydrologists understand that the watershed runoff process is a complex integration of saturation overland flow and infiltration excess (Hortonian) overland flow (Troendle, 1985). Areas that generate surface runoff pulsate, shrink and expand in response to rainfall. This concept on a watershed scale is consistent with the hill slope hydrologic processes.

Increased Runoff Volume, Velocity, Peak Flow, etc. Changes in land use cause runoff volumes to increase and groundwater recharge to decrease. Wetlands and first order streams reflect changes in groundwater levels most profoundly, and this reduced flow can stress or even eliminate the aquatic community. **As the most hydrologically and biologically sensitive elements of the drainage network, headwaters and first order streams warrant special consideration and protection in stormwater management.**

Flooding. Flooding accounts for larger annual property losses than any other single geophysical hazard (Riley, 1985) (**Figure 4.12**). While some overbank flooding is inevitable and even desirable, the historical goal of drainage design in most of Virginia has been to maintain pre-development peak discharge rates for both the two- and ten-year frequency storms after development, aiming to keep the level of overbank flooding the same over time. This prevents costly damage or maintenance for culverts, drainage structures, and swales, as well as damage to personal property.

Figure 4.12. Flooding

Rainfall events, or *storms*, are typified by their total rainfall, time-span, and the average and peak intensity and are ranked in terms of the statistical frequency of their return interval (NRC 2008). For example, a storm that has a 50% chance of occurring in any given year is termed a "two-year" storm. Traditionally, the two-year storm has also considered to represent the typical bankfull flow of a stream channel (research has demonstrated that most natural stream channels in the State have just enough capacity to carry the two-year flow without spilling onto the floodplain). In Virginia, a two-year storm produces from approximately 2.5 - 5.2 inches of rain in a 24-hour period, depending on the physiography and prevailing weather patterns. Less annual rainfall occurs in the ridge and valley province, with more in the Piedmont. Southeastern Virginia and the eastern slopes of the Blue Ridge always experience the most annual rainfall. The majority of the state experiences from 3.2 - 3.6 inches of rain from a two-year 24-hour storm (NOAA Atlas 14). This rainfall depth is called the two-year design storm.

In recent years, scientists have conducted much research on stream channels to improve their understanding of how channels are formed naturally and how degraded channels can be restored to their natural equilibrium. The research indicates that channel forming flows vary, depending upon the channel's setting in the landscape. Stream channels in urban areas may be formed by flows as little as the 0.9-year storm, whereas channels in rural areas are typically formed by the 1.5-year to 1.7-year storm. However, the channel-forming storm varies with each stream channel, depending on a number of physical characteristics. Fortunately, scientists have determined methods for determining the channel-forming storm level for any particular stream section. For regulatory purposes, most states have begun to establish the one-year 24-hour storm event as the average channel-forming storm. In Virginia, a one-year storm produces from approximately 1.9 - 3.2 inches of rain in a 24-hour period. However, the majority of the state experiences from 2.6 - 3.0 inches of rain from a one-year 24-hour storm (NOAA Atlas 14). This rainfall depth is called the one-year design storm.

Similarly, a storm that has a 10% chance of occurring in any given year is termed a ten-year storm. In Virginia, a ten-year storm produces from approximately 3.5 - 8 inches of rain in a 24-hour period. However, the majority of the state experiences from 4.8 - 5.5 inches of rain from a ten-year 24-hour storm (NOAA Atlas 14). Under traditional engineering practice, most channels and storm drains in Virginia are designed with enough capacity to safely pass the peak discharge from a ten-year design storm.

The Committee on Reducing Stormwater Discharge Contributions to Water Pollution and common sense indicate that accurate and well-maintained long-term records of precipitation are "vital and nontrivial" to stormwater regulation. For a network of precipitation gauge data, visit the National Climatic Data Center online at http://www.ncdc.noaa.gov/oa/ncdc.html or the Cooperative Weather Observer Program at http://www.nws.noaa.gov/om/coop/. Additionally, the National Weather Service offers a service that estimates the return period for a range of depth-duration events. It can be found at http://www.nws.noaa.gov/om/coop/. Considering the implications of climate change previously mentioned, such that precipitation regimes are systematically being altered, it is paramount to update depth-duration-frequency curves in order to guarantee stormwater management facilities will be able to accommodate more intense precipitation.

The combination of more runoff more often and at higher rates will create localized flooding and damage, even in small storm events. Flows that exceed the capacity of the stream channel spill over onto adjacent floodplains. These are termed *overbank* floods. They can damage property and downstream drainage structures. In many watersheds throughout the state, flooding problems have increased over time due to the changes in land use and ineffective stormwater management. This increase in stormwater volume is the direct result of more extensive impervious surface areas, combined with substantial tracts of natural landscape being converted to lawns on highly compacted soil.

Figures 4.13-a and 4.13-b depict typical pre-development and post-development streamflow hydrographs for a developed watershed.

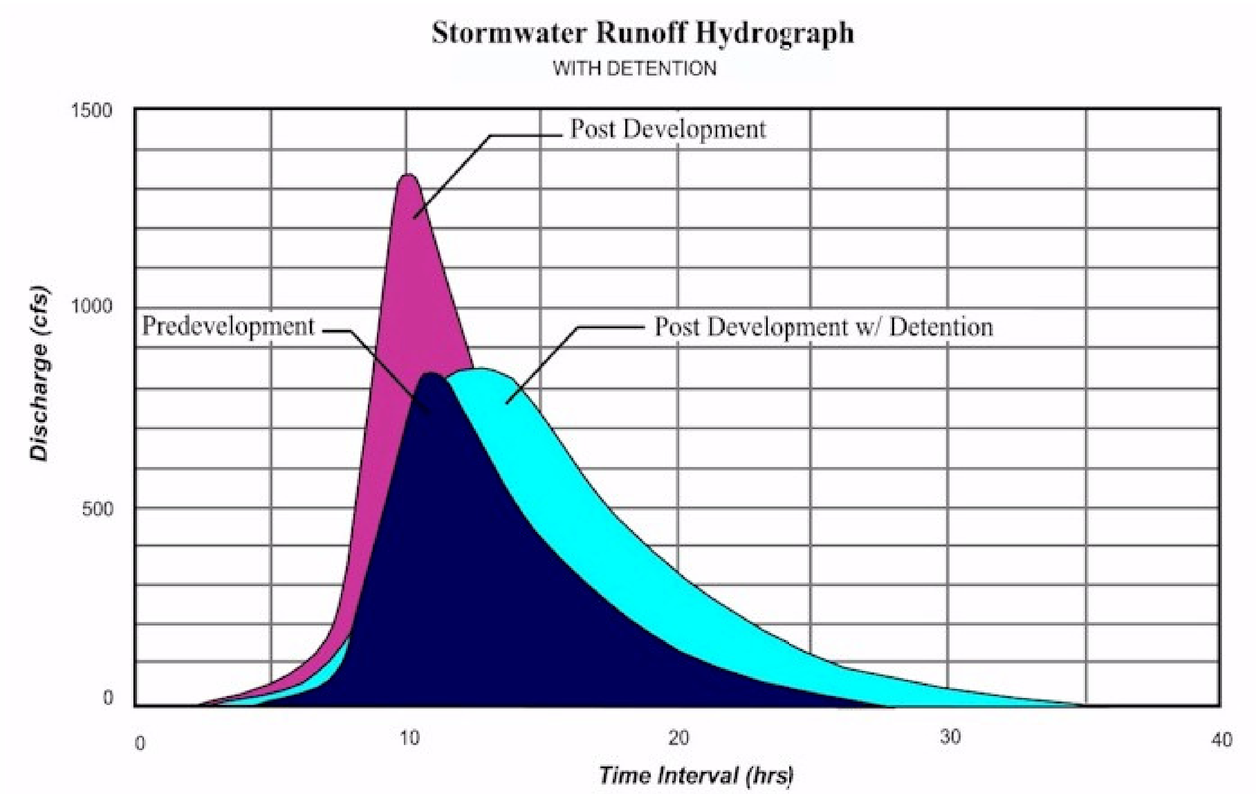
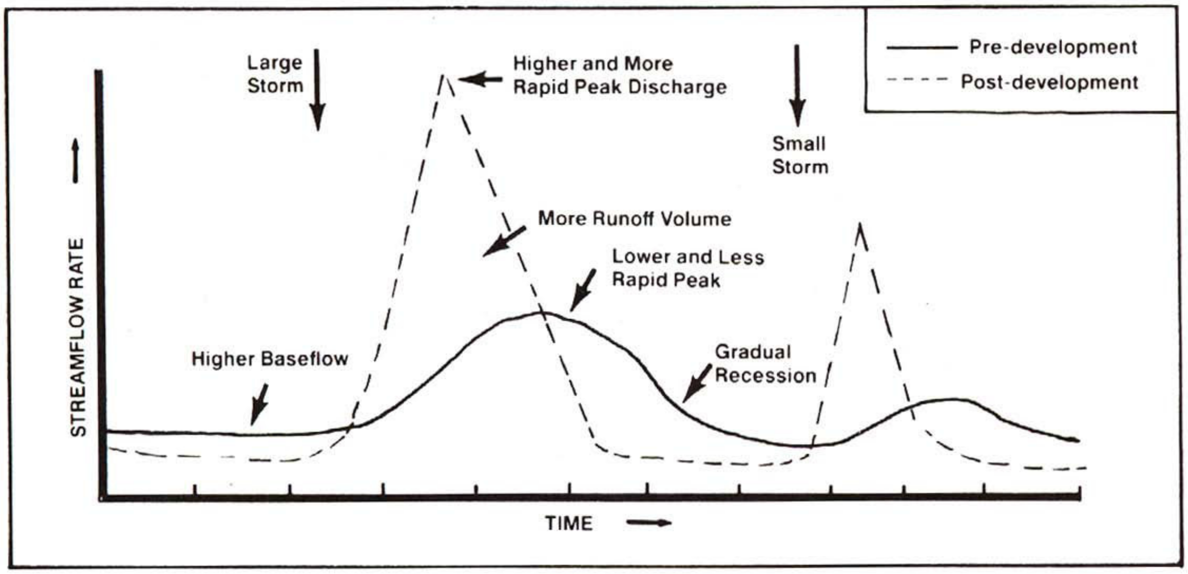


Figure 4.13-a. Pre- and Post-Development Stormwater Runoff Hydrographs



Alternate Figure 4.13-b. Stormwater Runoff Hydrograph Comparisons

4.5.1.2 Stream Channel and Floodplain Impacts

Stream channels in urban areas respond to and adjust to the altered hydrologic regime that accompanies urbanization. The severity and extent of stream adjustment is a function of the degree of watershed imperviousness (WEF and ASCE, 1998).

The impacts of development on stream channels and floodplains may include:

- Channel erosion/scour, widening, and downcutting
- Increased sediment loads
- Shifting bars of coarse sediment
- Degradation of stream habitat
- Loss of pool/riffle structure and sequence
- Burying of stream substrate
- Decline in diversity of aquatic insects and freshwater mussels
- Decline in diversity of fish
- Man-made stream enclosure or channelization
- Floodplain expansion

Channel Erosion, Widening, and Downcutting**.** Increased stormwater runoff volume can turn small meandering streams into highly eroded and deeply incised stream channels. Stream meander and the resulting erosion and sedimentation are natural processes, and all channels are in a constant process of incremental alteration. However, as the runoff volume from each storm is increased, natural stream channels experience more frequent bank-full or nearly bank-full conditions. As a result, streams change their natural shape and form (**Figure 4.14**). The majority of this stream channel devastation is intensified during the frequently occurring small-to-moderate rainfall events, not during major flooding events.

Figure 4.14. Stream Channel Erosion

The shape of a stream channel, its width, depth, slope, and how it moves through the landscape, is influenced by the amount of flow the stream channel is expected to carry. The stream channel geometry *(morphology)* is determined by the energy of typical stream flows ranging from "low flow" to "bankfull". The flow depths determine the energy of the water in the stream channel, and this energy shapes the channel itself.

In an undeveloped watershed, bankfull flow occurs with a frequency of approximately once every 18-21 months. During bankfull flows, the speed (velocity) of the water flow is typically at its maximum. If these high-velocity flows last long enough or occur often enough, they can generate enough energy to scour soil from streambanks and transport sediment and rocks from the stream bottom. During larger flood events, the flow overtops the stream banks and flows into the floodplain. As the flow spreads out, velocity is reduced, resulting in much less impact on the shape of the stream channel itself.

In a developing watershed, bankfull flows occur more often. The volume and flow rate of stormwater runoff increase during small storm events and the stream channel changes to accommodate the greater flows. Because the stream is conveying greater flows more often and for longer periods of time, the stream will try to accommodate these larger flows by eroding stream banks or cutting down the channel bottom.

Traditionally, stormwater managers have used detention basins to capture (detain) excess stormwater runoff and release it over a period of days into the receiving stream channel. However, the release rate of flow from the basin typically mimics the bankfull flow. Stormwater rules have attempted to assure that runoff from development sites should not exceed the capacity of the receiving stream channel. In Virginia, this requirement has been translated into not exceeding a 2-year/24-hour design storm, which has been considered the bankfull storm. Virginia has required that the peak rate of discharge from the two-year storm applied to the post-development site conditions be reduced to the pre-development rate of discharge. The problem is that, unlike a normal "flashy" rainstorm, after which runoff flow recedes rather quickly, the outflow from a detention basin often exposes the channel to a longer duration of erosive flows than it would have otherwise received. This keeps the stream bed and banks wet and subject to high-velocity flows, which makes them more susceptible to erosion. Therefore, channel deterioration is often most pronounced downstream of detention basins or where similar stormwater management practices are placed as a result of land development.

Numerous studies have documented the link between altered stream channels and land development. The Center for Watershed Protection (Article 19, Technical Note 115, Watershed Protection Techniques 3(3): 729-734) states that land development influences both the morphology and stability of stream channels, causing downstream channels to enlarge through widening and stream bank erosion.

These physical changes, in turn, degrade stream habitat and produce substantial increases in sediment loads resulting from accelerated channel erosion. The typical stream bed structure of pools, riffles and meanders disappears, and the water temperature becomes much warmer.

As the shape of the stream channel changes to accommodate more runoff, aquatic habitat is often lost or altered, and aquatic species decline. Studies, such as US EPA's Urbanization and Streams: Studies of Hydrologic Impacts (1997), conclude that land development is likely to be responsible for dramatic declines in aquatic life observed in developing watersheds.

Degradation of Stream Habitat. The effects occur at many levels in the aquatic community. As the gravel stream bottom is covered in sediment, the amount and types of microorganisms that live along the stream bottom decline. The stream receives sediment from runoff, but additional sediment is generated as the stream banks are eroded and this material is deposited along the stream bottom, burying the substrate material of the stream bed. Pools and riffles important to fish and other aquatic life are lost, and the number and types of fish and aquatic insects diminishes. Stream channels become wide, deep, flat, and uniform. Because the channels are so much larger, low flows become much shallower. Trees and shrubs along the banks are undercut and lost, removing important habitat and decreasing natural shading and cooling for the stream, so the water becomes warmer. Just as weeds can invade and overwhelm preferable vegetation when conditions provide the opportunity, less desirable species begin to replace desirable species in degraded streams.

As an example of the economic impact of such degradation, the Center for Watershed Protection has provided a summary of 15 stream restoration projects in Maryland and Illinois ranging in length from 500 feet to 13,200 feet. These projects had costs ranging from $12,000 to $2.2 million per project. Streambank restoration projects can cost up to $100,000 per linear foot for concrete channelization, compared to $100 per linear foot for vegetative methods, such as reforesting the buffer area. In Fairfax County, a local bond issue provided nearly $1.5 million to restore two miles of degraded stream and riparian area (CBP, 1998).

Shoreline and bank erosion also eat away at property values. For example, using the hedonic price method, a statistical method for determining the prices of the individual attributes of properties, Van de Verg and Lent determined that property values for Chesapeake Bay shoreline homes in Maryland would decline on average $3,474 per annual foot of erosion (Van de Verg and Lent, 1994). In fact, many urban governments find themselves engineering degraded stream channels, straightening them and lining them with concrete, in order to prevent further erosion and speed the stormwater through their jurisdiction. Unfortunately, sooner or later that concrete channel ends, and the high-volume, high-velocity flows are released into a natural stream channel further downstream. This merely extends the damage into another part of the stream or another jurisdiction.

Floodplain Expansion. The level areas bordering streams and rivers are known as floodplains. Operationally, the floodplain is usually defined as the land area within the limits of the water elevation of the 100-year storm flow. The 100-year storm has a 1% chance of occurring in any given year. The 100-year storm typically serves as the basis for controlling development and establishing insurance rates by the Federal Emergency Management Agency (FEMA). In most of Virginia, a 100-year storm results in approximately 8 - 9 inches of rainfall in a 24-hour period. Floods of this scale can be very destructive and can pose a threat to human life. Floodplains are natural storage areas that help to attenuate downstream flooding.

Floodplains are very important habitat areas, encompassing riparian forests, wetlands, and wildlife corridors. Consequently, all local jurisdictions in Virginia restrict or even prohibit new development within the 100-year floodplain, to prevent flood hazards and conserve habitats. Nevertheless, prior development that has occurred in the floodplain remains subject to periodic flooding during these storms.

Development sharply increases the peak discharge rate associated with the 100-year design storm. As a consequence, the elevation of a stream’s 100-year floodplain becomes higher and the boundaries of its floodplain expand laterally (see **Figure 4.15**). In some instances, property and structures that had not previously been subject to flooding become at risk. Additionally, such a shift in a floodplain’s hydrology can degrade wetlands and forest habitats.

4.5.1.3 Water Quality Impacts

Urbanization increases the discharge of pollutants in stormwater runoff. Development introduces new sources of stormwater pollutants and provides impervious surfaces that accumulate pollutants between storms. Structural stormwater collection and conveyance systems allow stormwater pollutants to quickly wash off during rainfall or snowmelt events and discharge to downstream receiving waters. By contrast, in undeveloped areas, natural processes such as infiltration, interception, depression storage, filtration by vegetation, and evaporation can reduce the quantity of stormwater runoff and remove pollutants. Impervious areas decrease the natural stormwater purification functions of watersheds and increase the potential for water quality impacts in receiving waters.

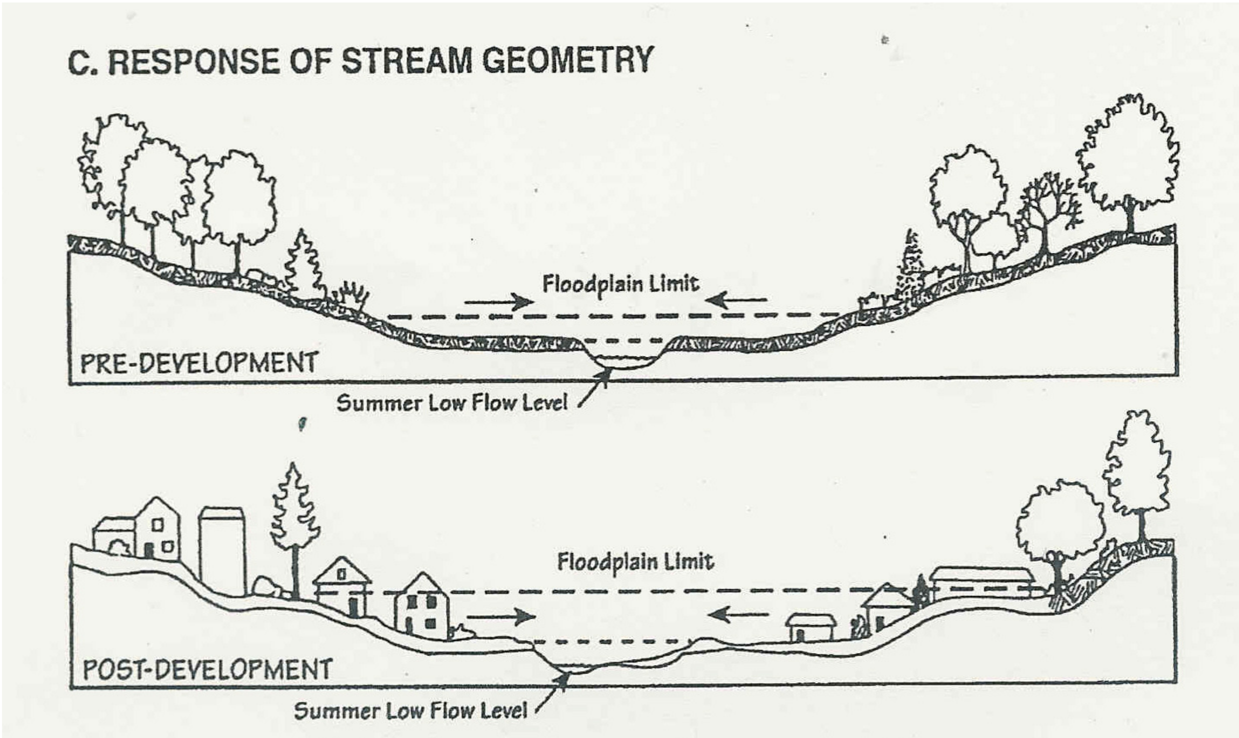


Figure 4.15. Response of Stream Geometry to Land Development

Urban land uses and activities can also degrade groundwater quality if stormwater with high pollutant loads is directed into the soil without adequate treatment. Certain land uses and activities, sometimes referred to as stormwater "hotspots" (e.g., commercial parking lots, vehicle service and maintenance facilities, and industrial rooftops), are known to produce higher loads of pollutants such as trace metals, petroleum hydrocarbons and toxic chemicals. Soluble pollutants can migrate into groundwater and potentially contaminate wells in groundwater supply aquifer areas. The potential for groundwater pollution from stormwater is even greater in regions of karst geologic formations, where seams and channels dissolved in the limestone base material can quickly transport pollutants into perched groundwater and deeper aquifers.

Impervious surfaces and maintained landscapes generate pollutants that are conveyed in runoff and discharged to surface waters. Many studies of pollutant transport in stormwater have documented that pollutant concentrations show a distinct increase at the beginning of a flow hydrograph referred to as the "*first flush*". In fact, the particulate associated pollutants that are initially scoured from the land surface and suspended in the runoff are generally observed in a stream or river before the runoff peak occurs. These pollutants include sediment, phosphorus that is moving with colloids (clay particles), metals, and organic particles and litter. However, dissolved pollutants may actually decrease in concentration during heavy runoff. These include nitrate, salts and some synthetic organic compounds applied to the land for a variety of purposes.

Many areas assumed to be pervious, such as chemically maintained lawns and landscaped areas, also add significantly to the pollutant load, especially where these pervious areas drain to impervious surfaces and storm sewers. The compacted soils at many land development sites result in vegetated surfaces that are close to impervious in many instances, producing far more runoff than the natural (pre-development) soil did. These new lawn surfaces are often loaded with fertilizers that result in polluted runoff that degrades downstream streams, ponds and lakes.

On average, protecting water quality is less costly than restoring or treating water after it has been contaminated. The average annual federal cost of reducing nonpoint source inputs of nitrogen, phosphorus, and sediment to Highland Silver Lake in southwest Illinois was estimated to be $3,000 - 9,000 per percentage point of reduction in pollutant loading for non-structural practices. Compare this to the cost of structural treatment practices, such as impoundments, which can be greater than $59,000 per percentage point (Setia and Magelby, 1988). Lake restoration costs can be even greater than the cost of water quality protection practices, and they will vary depending on the technique used as well as the characteristics of the lake. For example, alum addition can cost $14,000 per 100 tons. Shading and sediment covers can range from $1,375 - 65,475 per acre. Plant harvesting costs on average $140 - 310 per acre (USEPA, 1990). Often more than one technique must be used to restore a body of water, which may raise the cost significantly. The estimated cost of filtration of New York's Catskill/Delaware water supply is $4.57 billion (Aponte Clarke and Stoner, 2001).

Another example of the negative economic impact of stormwater pollution is the fisheries industry. The total economic value of commercial fishing in the Chesapeake Bay was estimated in 1989 by the state of Maryland to be $520 million per year (in 1987 dollars). In 1999, 460 million pounds of fish valued at $108 million were landed in Virginia. Particularly important in Virginia were oysters and blue crabs. In 1999, blue crabs brought in $21 million while the eastern oyster generated $967,000.

This income from fisheries can quickly decline when water quality declines. Pollutants can contaminate or suffocate fish, as well as degrade fish habitat. In 1989 the USEPA estimated that stormwater runoff costs the commercial fish and shellfish industries approximately $17 million to $31 million per year. Nitrogen and phosphorus are often associated with stormwater runoff, and high levels of these nutrients have been linked to fish kills caused by the toxic dinoflagellete *pfiesteria piscicda.* According to the Maryland Sea Grant Extension Program, *pfiesteria* cost the Chesapeake Bay seafood industry $43 million in 1997, and the recreational fishing industry $4.3 million.

Particulates and Solutes. One very important distinction for stormwater pollutants is the extent to which the pollutants exist in a solid (*particulate*) form, or are dissolved in the runoff (as *solutes*). The best example of this comparison is the two common fertilizers: Total phosphorus (TP) and nitrate (NO_3-N). Phosphorus typically occurs in particulate form, usually bound to colloidal soil particles. Because of this physical form, stormwater management practices that rely on physical filtering and/or settling of sediment particles can be quite successful for phosphorus removal. In stark contrast, nitrate tends to occur in highly soluble forms, and is unaffected by many of the structural BMPs designed to eliminate suspended pollutants. As a consequence, stormwater management BMPs for nitrate may be quite different than those used for phosphorous removal. Non-structural treatment practices may in fact be the best at removing nitrate from runoff.

Particulates**:** Stormwater pollutants that move in association with or attached to solid particles include total suspended solids (TSS), total phosphorus (TP), most organic matter (as estimated by COD), metals, and some herbicides and pesticides. Kinetic energy keeps particulates in suspension and some do not settle out easily. For example, an extended detention basin offers a good method to reduce total suspended solids, but is less successful with TP, because much of the TP load is attached to fine clay particles that may take longer to settle out.

If the concentration of particulate-associated pollutants in stormwater runoff, such as TSS and TP, is measured in the field during a storm event, a significant increase in pollutant concentration corresponding to but not synchronous with the surface runoff hydrograph is usually observed (**Figure 4.16**). This change in pollutant concentration is referred to as a "chemograph", and its pattern has helped to stimulate the concept of a "first flush" of stormwater pollutants. In fact, the actual transport process of stormwater pollutants is somewhat more complex than "first flush" would indicate, and has been the subject of numerous technical papers (Cahill et al, 1974: 1975; 1976; 1980; Pitt, 1985, 2002).

Because most of the particulate-associated pollutants are transported with the smallest particles (or *colloids*), their removal by stormwater control measures (SCMs) is especially difficult. These colloids are so small that they do not settle out in a quiescent pool or basin, but remain in suspension for days at a time, passing through detention basins with the outlet discharge. It is possible to add chemicals to a detention basin to coagulate these colloids to promote settling, but this chemical use turns a natural stream channel or pond into a treatment unit, and subsequent removal of sludge is required. A variety of STPs have been developed that serve as runoff filters, and are designed for installation in storm sewer elements, such as inlets, manholes or boxes. The potential problem with all measures that attempt to filter stormwater is that they quickly become clogged, especially during major storm events. Of course, one could argue that if the filter systems become clogged, they are performing efficiently, and removing this particulate material from the runoff. However, this means that substantial maintenance is required for all filtering (and to some extent settling) measures. The more numerous and distributed these STPs are within the built conveyance system, the greater the removal efficiency, but also the greater the cost for operation and maintenance.

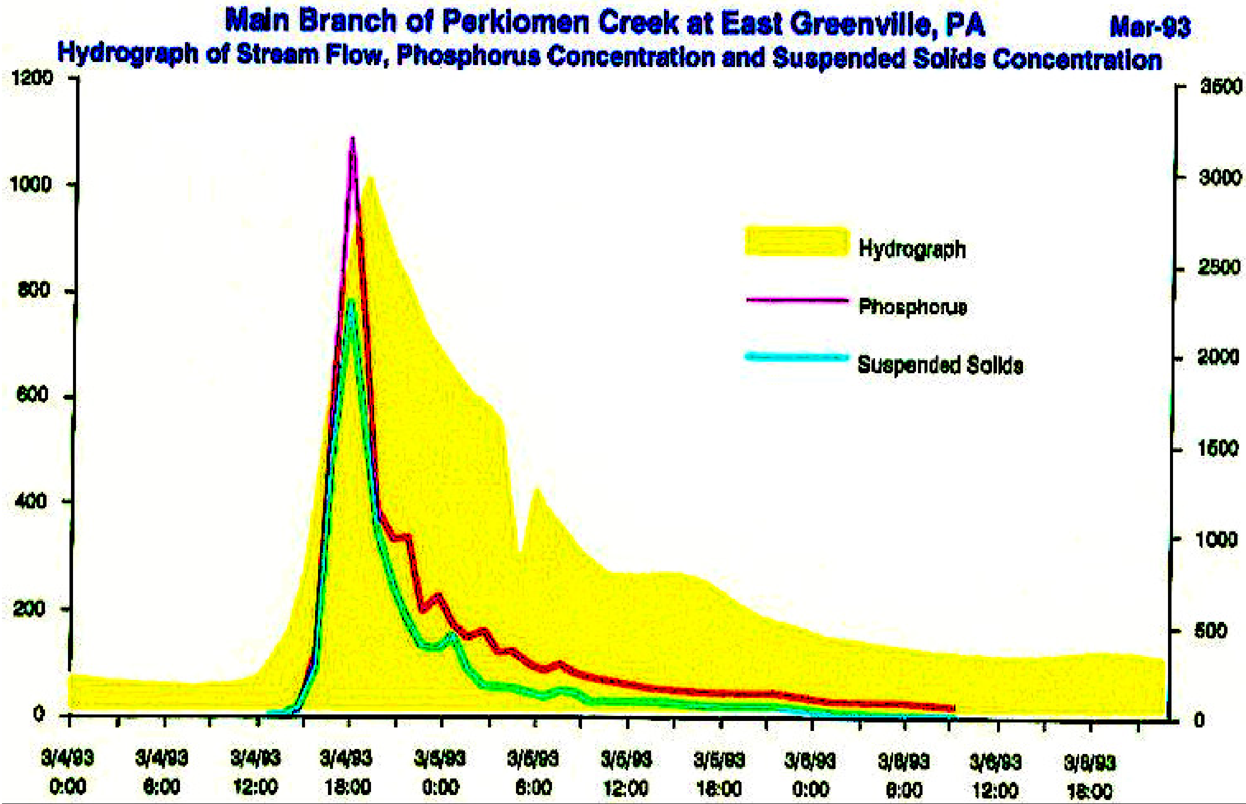


Figure 4.16. Chemograph of phosphorus and suspended solids in Perkiomen Creek (Cahill, 1993).

<u>Solutes</u>**:** Dissolved stormwater pollutants generally do not exhibit any increase during storm event runoff, and in fact may exhibit a slight dilution over a given storm hydrograph. Dissolved stormwater pollutants include nitrate, ammonia, salts, organic chemicals, many pesticides and herbicides, and petroleum hydrocarbons (although portions of the hydrocarbons may bind to particulates and be transported with TSS). Regardless, the total mass transport of soluble pollutants is dramatically greater during runoff because of the volume increase. In some watersheds, the stormwater transport of soluble pollutants can represent a major portion of the total annual load for a given pollutant, even though the absolute concentration remains relatively constant.

Some dissolved stormwater pollutants can be found in the initial rainfall, especially in regions with significant emissions from fossil fuel plants. Precipitation serves as a "scrubber" for the atmosphere, removing both fine particulates and gases – Nitrogen Oxide (NOX) and Sulpher Dioxide (SOX). Chesapeake Bay scientists have measured rainfall with Nitrate (NO_3) concentrations of 1-2 mg/L, which could comprise a significant fraction of the total input to the Bay. Other rainfall studies by NOAA and USGS have resulted in similar conclusions. Impervious pavements can transport nitrates, reflecting a mix of deposited sediment, vegetation, animal wastes, and human detritus of many different forms.

Table 4.5 lists the main pollutants found in urban stormwater runoff, typical pollutant sources, related impacts to receiving waters, and factors that promote pollutant removal. The Table also identifies the pollutants that commonly occur in dissolved or soluble form, which has important implications for the selection and design of stormwater treatment practices. Concentrations of pollutants in stormwater runoff vary considerably between sites and storm events.

Typical average pollutant concentrations in urban stormwater runoff in the Northeast United States are summarized in **Table 4.6.** More detailed descriptions of those pollutant categories follow the Tables.

Excess Nutrients. Urban stormwater runoff typically contains elevated concentrations of nitrogen and phosphorus that are most commonly derived from lawn fertilizer, detergents, animal waste, atmospheric deposition, organic matter, and improperly installed or failing septic systems. Elevated nutrient concentrations in stormwater runoff can result in excessive growth of vegetation or algae in streams, lakes, reservoirs, and estuaries, a process known as accelerated eutrophication. Phosphorus is typically the growth-limiting nutrient in freshwater systems, while nitrogen is growth-limiting in estuarine and marine (saltwater) systems. This means that in marine waters algal growth usually responds to the level of nitrogen in the water, and in fresh waters algal growth is usually stimulated by the level of available (soluble) phosphorus (Connecticutt DEP, 1995). Urban runoff has been defined as a key and controllable source of nutrients by the USEPA Chesapeake Bay Program. Virginia has committed to reducing tributary loadings of phosphorus and nitrogen from developing lands by 6,080,971 lbs. per year and 65,888,583 lbs. per year, respectively (VASECNATRES, 2005).

Nutrients are a major source of degradation in many of Virginia’s water bodies. Excessive nitrogen loadings have led to hypoxia, a condition of low dissolved oxygen, in the Chesapeake Bay and the lower reaches of some of Virginia’s major rivers. Phosphorus in runoff has impacted the quality of many of Virginia’s lakes and ponds, which are susceptible to eutrophication from phosphorus loadings. Nutrients are also detrimental to submerged aquatic vegetation (SAV). Nutrient enrichment can favor the growth of epiphytes (small plants that grow attached to other things, such as blades of eelgrass) and increase amounts of phytoplankton and zooplankton in the water column, thereby decreasing available light for the SAV. Excess nutrients can also favor the growth of macroalgae, which can dominate and displace eelgrass beds and dramatically change the food web (Deegan et al., 2002).

Table 4.5. Summary of Urban Stormwater Pollutants

Stormwater Pollutant	Potential Sources	Receiving Water Impacts	Removal Promoted by[1]
Excess Nutrients Nitrogen, Phosphorus (soluble)	Animal waste, fertilizers, failing septic systems, landfills, atmospheric deposition, erosion and sedimentation, illicit sanitary connections	Algal growth, nuisance plants, ammonia toxicity, reduced clarity, oxygen deficit (hypoxia), pollutant recycling from sediments, decrease in submerged aquatic vegetation (SAV)	Phosphorus: High soil exchangeable aluminum and/or iron content, vegetation and aquatic plants Nitrogen: Alternating aerobic and anaerobic conditions, low levels of toxicants near neutral pH (7)
Sediments Suspended, dissolved, sorbed pollutants **(add term to glossary)**	Construction sites, stream bank erosion, washoff from impervious surfaces	Increased turbidity, lower dissolved oxygen, deposition of sediments, aquatic habitat alteration, sediment and benthic toxicity	Low turbulence, increased residence time
Pathogens Bacteria, viruses	Animal waste, failing septic systems, illicit sanitary connections	Human health risk via drinking water supplies, contaminated swimming beaches, and contaminated shellfish consumption	High light (ultraviolet radiation), increased residence time, media/soil filtration, disinfection
Organic Materials Biochemical oxygen demand (BOD), chemical oxygen demand (COD)	leaves, grass clippings, brush, failing septic systems	Lower dissolved oxygen, odors, fish kills, algal growth, reduced clarity	Aerobic conditions, high light (ultraviolet radiation), high soil organic content, low levels of toxicants, near neutral pH (&)
Hydrocarbons Oil and grease	Industrial processes, commercial processes, automobile wear, emissions, and fluid leaks, improper oil disposal	Toxicity of water column and sediments, bioaccumulation in food chain organisms	Low turbulence, increased residence time, physical separation or capture technique
Metals Copper, lead, zinc, mercury, cadmium, chromium, nickel, aluminum (soluble)	Industrial processes, normal wear of automobile brake linings and tires, automobile emissions and fluid leaks, metal roofs and pipes	Toxicity of water column and sediments, bioaccumulation in food chain organisms	High soil organic content, high soil cation exchange capacity, near neutral pH (7)
Synthetic Organic Chemicals Pesticides, VOCs, SVOCs, PCBs, PAHs (soluble)	Residential, commercial, and industrial application of herbicides, insecticides, fungicides, rodenticides, industrial processes, commercial processes	Toxicity of water column and sediments, bioaccumulation in food chain organisms	Aerobic conditions, high light (ultraviolet radiation), high soil organic content, low levels of toxicants, near neutral pH (7), high temperature and air movement for volatilization of VOCs
Deicing Constituents Sodium chloride, calcium chloride, potassium chloride, ethylene glycol, other pollutants (soluble)	Road salting and uncovered salt storage, snowmelt runoff from snow piles in parking lots and along roads during the spring snowmelt season or during winter rain and snow events	Toxicity of water column and sediments, contamination of drinking water, harmful to salt-intolerant plants; concentrated loadings of other pollutants as a result of snowmelt	Aerobic conditions, high light (ultraviolet radiation), high soil organic content, low levels of toxicants, near neutral pH (7)
Trash and Debris	Litter washed through the storm drain networks	Degradation of aesthetics, threat to wildlife, potential clogging of storm drainage systems	Low turbulence, physical straining/capture
Freshwater Impacts	Stormwater discharges to tidal wetlands and estuarine environments	Dilution of the high marsh salinity and encouragement of the invasion of brackish or upland wetland species, such as Phragmites	Stormwater retention and volume reductions
Thermal Impacts	Runoff with elevated temperatures from contact with impervious surfaces (asphalt)	Adverse impacts to aquatic organisms that require cold and cool water conditions	Use of wetland plants and trees for shading, increased pool depths

[1] Factors that promote removal of most stormwater pollutants include: (1) Increasing hydraulic residence time; (2) Low turbulence; (3) Fine, dense, herbaceous plants; and (4) Medium-fine textured soil

Source: Adapted from Connecticutt DEP, 1995, Metropolitan Council, 2001; Watershed Management Institute, Inc., 1997

Table 4.6. Average Pollutant Concentrations in Urban Stormwater Runoff [1]

Constituent	Units	Concentration
Total Suspended Solids (TSS)	mg/l	54.5
Total Phosphorus (TP) [2]	mg/l	0.23 - 0.28 (0.26)
Soluble Phosphorus [2]	mg/l	0.10
Total Nitrogen (TN) [2]	mg/l	1.12 - 2.68 (2.00)
Total Kjeldahl Nitrogen (TKN) [2]	mg/l	1.47
Nitrite and Nitrate [2]	mg/l	0.53
Cadmium [3]	:g/l	2
Copper [2]	:g/l	11.1
Lead [2]	:g/l	50.7
Zinc [2]	:g/l	129
BOD [2]	mg/l	11.5
COD [2]	mg/l	44.7
Organic Carbon [4]	mg/l	11.9
PAH [5]	mg/l	3.5
Oil and Grease [6]	mg/l	3.0
Fecal Coliform [7]	Colonies/100 ml	15,000
Fecal Strep [7]	Colonies/100 ml	35,400
Chloride (snowmelt) [8]	mg/l	116

Units: mg/l = milligrams per liter; :g/l = micrograms per liter
[1] These concentrations represent *mean* or *median* concentrations in stormwater runoff measured at typical sites and may be greater during individual storms. Also note that mean or median runoff concentrations from *stormwater hotspots* are 2-10 times higher than those shown here.
Sources: Adapted from New York DEC, 2001; original sources listed as follows: [2] Pooled Nationwide Urban Runoff Program/USGS (Smullen and Cave); [3] USEPA, 1983; [4] Derived from National Pollutant Removal Database (Winer, 2000); [5] Rabanal and Grizzard, 1996; [6] Crunkilton et al., 1996; [7] 65 Schueler, 1999; [8] Oberts, 1994

Sediments/Suspended Solids. Sediment loading to water bodies occurs from washoff of particles that are deposited on impervious surfaces such as roads and parking lots, soil erosion associated with construction activities, and streambank erosion. Although some erosion and sedimentation is natural, excessive sediment loads can be detrimental to aquatic life including phytoplankton, algae, benthic invertebrates, and fish, by interfering with photosynthesis, respiration, growth, and reproduction. Solids can either remain in suspension or settle to the bottom of the water body. Suspended solids can make the water cloudy or turbid, detract from the aesthetic and recreational value of a water body, and harm SAV, finfish, and shellfish. Sediment transported in stormwater runoff can be deposited in a stream or other water body or wetland and can adversely impact fish and wildlife habitat by smothering bottom dwelling aquatic life and changing the bottom substrate. Sediment deposition in water bodies can result in the loss of deep-water habitat and can affect navigation, often necessitating dredging. Sediment transported in stormwater runoff can also carry other pollutants such as nutrients, metals, pathogens, and hydrocarbons.

The following example illustrates the cost of sediment loading to a downstream reservoir during one year from active construction at a 100-acre mixed-use site. The Simple Method (Schueler, 1987) was used to calculate the sediment load in pounds per year from the construction site, assuming 40 inches of annual rainfall, 0.9 effective precipitation value, a runoff coefficient of 0.5 for the construction site, and an event mean concentration (EMC) of 15,000 mg/L (taken from Owens, *et al.*, 2000). Using 100 pounds per cubic foot as the dry density of the sediment, the volume of sediment entering the reservoir during one year was determined to be 2,267 cubic yards. Assuming a cost of $20 per cubic yard for dredging, transport, and disposal of this sediment, the annual cost would be $45,340 to remove the sediment generated from one source alone. If other sources of sediment to the reservoir were accounted for, this cost would rise significantly.

***Pathogens*.** Pathogens are bacteria, protozoa, and viruses that can cause disease in humans. The presence of bacteria, such as fecal coliform or enterococci, is used as an indicator of pathogens and of potential risk to human health (Connecticutt DEP, 1995). Pathogen concentrations in urban runoff routinely exceed public health standards for water contact recreation and shellfish harvesting. Sources of pathogens in stormwater runoff include animal waste from pets, wildlife, and waterfowl; combined sewer overflows; failing septic systems; and illegal sanitary sewer cross-connections. High levels of indicator bacteria in stormwater have commonly led to the closure of beaches and shellfish beds along coastal areas of Virginia.

***Organic Materials*.** Oxygen-demanding organic substances, such as grass clippings, leaves, animal waste, and street litter, are commonly found in stormwater. The decomposition of such substances in water bodies can deplete oxygen from the water, thereby causing effects similar to those caused by nutrient loading. Organic matter is of primary concern in water bodies where oxygen is not easily replenished, such as slower moving streams, lakes, and estuaries. It is a particular concern in the Chesapeake Bay because of the Bay's average depth is unusually shallow. An additional concern for unfiltered water supplies is the formation of trihalomethane (THM), a carcinogenic disinfection byproduct generated by the mixing of chlorine with water high in organic carbon (New York DEC, 2001).

***Hydrocarbons*.** Vehicles leak oil and grease that contain a wide array of hydrocarbon compounds. Urban stormwater runoff gathers up these hydrocarbons, some of which are toxic to aquatic organisms at low concentrations (Woodward- Clyde, 1990). The primary sources of hydrocarbons in urban runoff are automotive. Source areas with high concentrations of hydrocarbons in stormwater runoff include roads, parking lots, gas stations, vehicle service stations, residential parking areas, and bulk petroleum storage facilities.

***Trace Metals*.** Metals such as copper, lead, zinc, mercury, and cadmium are commonly found in urban stormwater runoff. Chromium and nickel are also frequently present (USEPA, 1983). The primary sources of these metals in stormwater are vehicular exhaust residue, fossil fuel combustion, corrosion of galvanized and chrome-plated products, roof runoff, stormwater runoff from industrial sites, and the application of deicing agents. Architectural copper associated with building roofs, flashing, gutters, and downspouts has been shown to be a source of copper in stormwater runoff (Barron, 2000; Tobiason, 2001). Marinas have also been identified as a source of copper and aquatic toxicity to inland and marine waters (Sailer Environmental, Inc. 2000). Washing or sandblasting of boat hulls to remove salt and barnacles also removes some of the bottom paint, which contains copper and zinc additives to protect hulls from deterioration. Discharge of metals to surface waters is of particular concern. Metals can be toxic to aquatic organisms, can bio-accumulate, and have the potential to contaminate drinking water supplies.

Although metals generally attach themselves to the solids in stormwater runoff or receiving waters, recent studies have demonstrated that dissolved metals – particularly copper and zinc – are the primary toxicants in stormwater runoff from industrial facilities (Mas et al., 2001; New England Bioassay, Inc., 2001). Additionally, stormwater runoff can contribute to elevated metals in aquatic sediments. The metals can become bio-available where the bottom sediment is anaerobic (without oxygen), such as in a lake or estuary. Metal accumulation in sediments has resulted in impaired aquatic habitat and more difficult maintenance dredging operations in estuaries, where the contaminated sediments require special handling.

***Pesticides/Synthetic Organic Chemicals*.** Synthetic organic chemicals can also be present at low concentrations in urban stormwater. Pesticides, phenols, polychlorinated biphenyls (PCBs), and polynuclear or polycyclic aromatic hydrocarbons (PAHs) are the organic compounds most frequently found in stormwater runoff. Such chemicals can exert varying degrees of toxicity to aquatic organisms and can bio-accumulate in fish and shellfish. Toxic organic pollutants are most commonly found in stormwater runoff from industrial areas. Pesticides are commonly found in runoff from urban lawns and street or road rights-of-way (New York DEC, 2001). A review of monitoring data on stormwater runoff quality from industrial facilities has shown that PAHs are the most common organic toxicants found in roof runoff, parking area runoff, and vehicle service area runoff (Pitt et al., 1995).

***Chlorides/Deicing Constituents*.** Salting of roads, parking lots, driveways, and sidewalks during winter months and snowmelt during the early spring result in the discharge of sodium, chloride, and other deicing compounds to surface waters via stormwater runoff. Excessive amounts of sodium and chloride may have harmful effects on water, soil and vegetation and can also accelerate corrosion of metal surfaces, which results in even more pollution. Drinking water supplies, particularly groundwater wells, may be contaminated by runoff from roadways where deicing compounds have been applied or from transportation agency facilities where salt mixes are improperly stored. In addition, sufficient concentrations of chlorides may prove toxic to certain aquatic species. Excess sodium in drinking water can lead to health problems in infants ("blue baby syndrome") and individuals on low sodium diets.

Other deicing compounds may contain nitrogen, phosphorus, and oxygen demanding substances. Deicing compounds can cause the release of other pollutants that had been trapped in ice or snow. The pollutant loading during snowmelt can be significant and can vary considerably during the course of the melt event (New York DEC, 2001). For example, a majority of the hydrocarbon load from snowmelt occurs during the last 10 percent of a winter storm event and towards the end of the snowmelt season (Oberts, 1994). Similarly, PAHs, which are hydrophobic materials, remain in the snowpack until the end of the snowmelt season, resulting in highly concentrated loadings (Metropolitan Council, 2001). Antifreeze from automobiles is a source of phosphates, chromium, copper, nickel, and cadmium. Other pollutants such as sediment, nutrients, and hydrocarbons are released from the snowpack during the spring snowmelt season and during winter rain-on-snow events.

Trash and Debris. Trash and debris are washed off of the land surface by stormwater runoff and can accumulate in storm drainage systems and receiving waters. Litter detracts from the aesthetic value of water bodies and can harm aquatic life and wildlife either directly (by being mistaken for food) or indirectly (by habitat modification). For example, many photos have appeared in various media of animals and birds trapped in a "necklace" of plastic that once held together a six pack of soft drinks. Sources of trash and debris in urban stormwater runoff include residential yard waste, commercial parking lots, street refuse, combined sewers, illegal dumping, and industrial refuse. Virginia citizens regularly participate in community river clean-ups focused on removing such debris from our waterways.

Thermal Impacts. When stream flow is comprised primarily of groundwater discharge, the constant cool temperature of the groundwater buffers variations in stream temperature. As the flow of groundwater decreases and the amount of surface runoff increases, the temperature regime of the stream changes. Runoff from impervious surfaces in the summer months can be much hotter than the stream temperature, and in the winter months this same runoff can be colder. These changes in temperature dramatically affect the aquatic habitat in the stream, ranging from the fish community that the stream can support to the microorganisms that form the foundation of the food chain. Important fungal communities can be lost altogether. It is apparent that increasing impervious areas can lead to significant degradation of surface water by altering the entire aquatic ecosystem.

Land clearing for development can reduce stream surface shading. Direct exposure of sunlight to shallow ponds and impoundments as well as unshaded streams may further elevate water temperatures. Elevated water temperatures can exceed fish and invertebrate tolerance limits, reducing survival and lowering resistance to disease. Coldwater fish such as trout may be eliminated, or the habitat may become marginally supportive of coldwater species when the water temperature rises only a few degrees. Studies have shown that when stream surface shade is reduced to 35%, trout populations can drop by as much as 85% (CBP, 1998; Galli, 1991). Stream and shoreline buffers also contribute to better water quality, which means better fish habitat and therefore more productive fisheries. Elevated water temperatures also contribute to decreased oxygen levels and dissolution of solutes in water bodies.

Freshwater Impacts. Discharge of freshwater, including stormwater, into brackish and tidal wetlands can alter the salinity and hydroperiod of these environments, which can encourage the invasion of brackish or freshwater wetland species such as Phragmites.

4.5.1.4 Habitat and Ecological Impacts.

Changes in hydrology, stream morphology, and water quality that accompany the development process can also impact stream habitat and ecology. A large body of research has demonstrated the relationship between urbanization and impacts to aquatic habitat and organisms. Habitat and ecological impacts may include:

- A shift from external (leaf matter) to internal (algal organic matter) stream production
- Reduction in the diversity, richness, and abundance of the stream community (aquatic insects, fish, amphibians)
- Destruction of freshwater wetlands, riparian buffers, and springs
- Creation of barriers to fish migration

4.5.1.5 Impacts on Other Receiving Environments.

The majority of research on the ecological impacts of urbanization has focused on streams. However, urban stormwater runoff has also been shown to adversely impact other receiving environments such as wetlands, lakes, and estuaries. Development alters the physical, geochemical, and biological characteristics of wetland systems. Lakes, ponds, wetlands, and SAV are impacted through deposition of sediment and particulate pollutant loads, as well as accelerated eutrophication caused by increases in nutrient loadings. Estuaries experience increased sedimentation and pollutant loads, and more extreme variations in salinity caused by increased runoff and reduced base flow. **Table 4.7** summarizes the effects of urbanization on these receiving environments.

Improperly managed stormwater causes increased flooding, water quality degradation, stream channel erosion, reduced groundwater recharge, and loss of aquatic species. But these and other impacts can be effectively avoided or minimized through better (environmental) site design. The problems caused by impervious and altered land surfaces can be avoided or minimized, but only by using stormwater management techniques that include runoff volume reduction, pollutant reduction, groundwater recharge and runoff rate control for virtually *all* storms. The aim must be to replicate the pre-development hydrology of the site as much as is feasible. The next chapter will provide guidance on how to accomplish this.

4.6 THE ECONOMIC BENEFITS OF GOOD STORMWATER MANAGEMENT

In 1989, the economic importance of the Chesapeake Bay was estimated to be $678 billion per year to the economies of Virginia and Maryland through commercial fishing, marine trade, recreation and tourism, port activities, and land values. While it is often difficult to calculate the "true" value of a water body or watershed, the above statistic shows that society often measures the value of these resources in terms of factors such as income from water-related activities, recreational pursuits, property values, and construction costs.

The irony of placing an economic value on water and other natural resources is that, for the most part, the services of these resources are freely available to those who wish to use them. However, poorly managed stormwater runoff from human activity, such as land development, can have negative impacts on water resources, such as the washing of pollutants into rivers and streams and creating sediment pollution downstream from eroding stream banks. Such consequences also have a negative *economic* impact on the value of these water resources to others who wish to use them. In this case, the person creating the negative impact is transferring at least part of the cost of carrying out his or her activities to the general public, who will end up paying the costs through taxes and user fees. For example, the USEPA estimated in 1998 that because of urban runoff pollution, hundreds of millions of dollars are lost each year through added government expenditures, illness, or loss of economic output.

Table 4.7. Effects of Urbanization on Other Receiving Environments

Receiving Environment	Impacts
Wetlands	! Changes in hydrology and hydrogeology ! Increased nutrient and other contaminant loads ! Compaction and destruction of wetland soil ! Changes in wetland vegetation ! Changes in or loss of habitat ! Changes in the community (diversity, richness, and abundance) of organisms ! Loss of particular biota ! Permanent loss of wetlands
Lakes and Ponds	! Impacts to biota on the lake bottom due to sedimentation ! Contamination of lake sediments ! Water column turbidity ! Aesthetic impairment due to floatables and trash ! Increased algal blooms and depleted oxygen levels due to nutrient enrichment, resulting in an aquatic environment with decreased diversity ! Contaminated drinking water supplies
Estuaries	! Sedimentation in estuarial streams and SAV beds ! Altered hydroperiod of brackish and tidal wetlands, which results from larger, more frequent pulses of fresh water and longer exposure to saline waters because of reduced flow ! Hypoxia ! Turbidity ! Bio-accumulation ! Loss of SAV due to nutrient enrichment and/or turbidity ! Scour of tidal wetlands and SAV ! Short-term salinity swings in small estuaries caused by the increased volume of runoff which can impact key reproduction areas of aquatic organisms

Source: Adapted from WEF and ASCE, 2998

There are two types of economic benefits of implementing sound stormwater management regulations and programs: (1) income generated by economic activities that rely on water and related natural resources; and (2) a reduction in or avoidance of costs which may result from environmental degradation and consumption of natural resources. These benefits are listed in **Table 4.8** (adapted from DCR and CWP, 2001).

The benefits listed above may be direct benefits, indirect benefits, or diversionary benefits. Direct benefits of water quality improvement include enhanced recreational water activities and reduced exposure to contaminants. Indirect benefits include enhancement of near-stream recreational activities, or the quality of residing, working, or traveling near water. Diversionary benefits include avoided water storage replacement costs and water treatment costs.

Table 4.8. Economic Benefits of Sound Stormwater Management

Watershed Protection Tool	Economic Benefit
Open Space Protection – forest conservation, wetland protection, preservation of parkland and open space	• Income from recreation and tourism • Increased property values • Reduction of energy costs, health care costs, flood control and stormwater quality and quantity treatment costs
Aquatic Buffers – Resource Protection Areas, stream buffers	• Enhanced aquatic habitat • Income from fishing • Increased property values • Reduction of flood control and stormwater quality and quantity treatment costs • Reduction of stream channel erosion and related degradation • Reduction of stream restoration costs
Better Site Design – cluster development, reduction of impervious cover, natural stormwater conveyances	• Increased property values • Reduction of construction, maintenance, and infrastructure costs • Reduction of flood control and stormwater quality and quantity treatment costs
Erosion and Sediment Control – channel protection, limiting clearing and grading, construction site erosion and sediment control	• Reduction of dredging costs • Improved income from marine and port activities • Reduction of drinking water treatment costs • Increased property values • Reduction of construction costs • Reduction of stream restoration costs
Stormwater Management Practices – stormwater management regulations, floodplain protection, etc.	• Increased property values • Reduction of flood damage costs • Reduction of flood control costs • Reduction of stream channel erosion and related degradation • Reduction of stream restoration costs • Improved water quality in our streams and rivers • Protected or improved aquatic habitat • Enhanced recreational opportunities • Lower water supply and laundry supply costs

References

Amandes, C. and Bedient, P., 1980, Stormwater Detention in Developing Watersheds, ASCE Journal of Hydraulics

Aponte Clarke, G. And N. Stoner. 2001. "Stormwater Strategies: The Economic Advantage." *Stormwater* 2(1): 10-18

Arnold, C.L., Jr., and C.J. Gibbons. 1996. "Impervious
Surface Coverage: The Emergence of a Key
Environmental Indicator". *Journal of the American Planning Association.* Vol. 62, No. 2.

Barnes, J. H., and W. D. Sevon, 1996. The Geologic Story of Pennsylvania, PA. Geological Survey, Educational Series No. 4, Harrisburg, PA

Barron, T. 2000. *Architectural Uses of Copper*: *An Evaluation of Stormwater Pollution Loads and Best Management Practices*. Prepared for the Palo Alto Regional Water Quality Control Plant.

Brown, Scott A., P.E., Larry A.J. Fennessey, Ph.D., P.E., and Gary W. Petersen, Ph.D., CPSS Understanding Hydrologic Process for Better Stormwater Management

Booth, D.B. and L.E. Reinelt. 1993. "Consequences of Urbanization on Aquatic Systems - Measured Effects, Degradation Thresholds, and Corrective Strategies", in *Proceedings of the Watershed '93 Conference*. Alexandria, Virginia.

Brant, T.R. 1999. "Community Perceptions of Water Quality and Management Measures in the Naamans Creek Watershed". Masters Thesis for the Degree of Master of Marine Policy.

Cahill, T. H., 1989. The Use of Porous Paving for Groundwater Recharge in Stormwater Management Systems. Floodplain/Stormwater Management Symposium, State College, PA, Oct., 1988.

Cahill, T. H., 1993. Stormwater Management Systems, Porous Pavement System with Underground Recharge Systems, Engineering Design Report, Spring, 1993.

Cahill, 1997. "Land Use Impacts on Water Quality: Stormwater Runoff." *Chesapeake Bay Restoration and Protection: Townships in the Lead*, Chesapeake Bay Local Government Advisory Committee, Pennsylvania Association of Township Supervisors, Harrisburg., PA. April 28, 1997.

Cahill, 1996. Sustainable Watershed Management: Balancing Water Resources and Land Use. W.R. Horner, T.H. Cahill and J. McGuire, Hydrology and Hydrogeology of Urban and Urbanizing Areas, Cahill Associates, West Chester, PA, April 21-24, 1996.

Cahill, et al., 1996. Sustainable Watershed Management in Developing Watershed. T. H. Cahill, J. McGuire, W. R. Horner, Cahill Assoc., West Chester, PA Am. Environment Congress, Anaheim, CA June 22-28, 1996.

Cahill, et al., 1996. Sustainable Watershed Management at the Rapidly Growing Urban Fringe. T. H. Cahill, J. McGuire, W. R. Horner, and R. D. Heister, at Watershed, 96, Balt. Conv. Ctr., Balt., MD. June 8-12, 1996.

Cahill, 1992. Limiting Nonpoint Source Pollution from New Development in the New Jersey Coastal Zone: Summary. T.H. Cahill, W.R. Horner, J.S. McGuire, and C. Smith, NJDEP; S. Whitney and S. Halsey, Cahill Assoc., West Chester, PA, September, 1992.

Cahill, 1992. Structural and Nonstructural Best Management Practices for the Management of Non-Point Source Pollution in Coastal Waters: A Cost-Effectiveness Comparison. T.H. Cahill and W.R. Horner, The Coastal Society; Thirteenth International Conference: Conference Proceedings Organizing for the Coast, Washington, D.C., April 1992.

Chesapeake Bay Program (CBP). 1998. *Economic Benefits of Riparian Forest Buffers*. Ref. 600.613.1 Fact Sheet.

Chorley, R.J. (1978). "The hillslope hydrologic cycle," *Hillslope Hydrology*, Edited by M.J. Kirby, Wiley, New York, NY, pp. 1-42

Center for Watershed Protection. 1999. Article 19, Technical Note 115, *Watershed Protection Techniques 3(3):* 729-734

Center for Watershed Protection (CWP). 2000b. *Urban Stream Restoration Practices: An Initial Assessment*.

Center for Watershed Protection (CWP). 2003. *Impacts of Impervious Cover on Aquatic Systems*. Watershed Protection Research Monograph No. 1. March 2003.

Connecticut Department of Environmental Protection (CTDEP). 1995. *Assessment of Nonpoint Sources of Pollution in Urbanized Watersheds: A Guidance Document for Municipal Officials, DEP Bulletin #22.* Bureau of Water Management, Planning and Standards Division, Hartford, Connecticut.

Connecticut Department of Environmental Protection (CTDEP). 2004 draft. *2004 List of Connecticut Water Bodies Not Meeting Water Quality Standards*.

Connecticut Department of Environmental Protection (CTDEP). *2004 Connecticut Stormwater Quality Manual*.

Crunkilton, R. et al. 1996. "Assessment of the Response of Aquatic Organisms to Long-Term Insitu Exposures of Urban Runoff", in *Effects of Watershed*

Day, G. E. and Crafton, C. S., 1978*, Site and Community Design Guidelines for Stormwater Management*, College of Architecture and Urban Studies, Virginia Tech.

Development and Management on Aquatic Ecosystems Proceedings of an Engineering Foundation Conference. Snowbird, Utah.

Deegan, L., A. A. Wright, S. G. Ayvazian, J. T. Finn, H. Golden, R. R. Merson, and J. Harrison. "Nitrogen loading alters seagrass ecosystem structure and support of higher trophic levels." *Aquatic Conservation*. 12(2): p. 193-212. March-April, 2002.

Emerson, C., Welty, C., Traver, R., 2005, A Watershed—scale Evaluation of a System of Stormwater Detention Basins, ASCE Journal of Hydraulic Engineering

Fenneman, N. M., 1938. Physiography of Eastern United States, McGraw-Hill Book Co., New York, NY.

Fennessey, Lawrence A. J., Ph.D., P.E. and Arthur C. Miller, Ph.D., P.E. 2001. Hydrologic Processes During Non-Extreme Events in Humid Regions

Fennessey, Lawrence A.J., Ph.D., P.E. and Richard H. Hawkins, Ph.D., P.E. 2001. The NRCS Curve Number: A New Look at an Old Tool

Firehock, K., and J. Doherty. 1995. *A Citizen's Streambank Restoration Handbook.* Gaithersburg, MD. Save Our Streams Program, Izaak Walton League of America, Inc.

Friedman, D.B., 2001. "Impact of Soil Disturbance During Construction on Bulk Density and Infiltration in Ocean County, New Jersey." Ocean County Soil Conservation District. Forked River, NJ

Friedman, D.B., "Developing an Effective Soil Management Strategy." Ocean County Soil Conservation District. Forked River, NJ.

Godfrey, M. A., 1997. Field Guide to the Piedmont, The University of North Carolina Press, Chapel Hill, NC.

Garthwaite, A., et al., *Water*. 2007, Credit Suisse: New York, NY.

Hanks, D & A. Lewandowski, 2003. Protecting Urban Soil Quality: Examples for Landscape Codes and Specifications, USDA-NRCS, Toms River, NJ

Heaney, J. Principles of integrated urban water management. Innovative Urban Wet-Weather Flow Management Systems. Pgs. 36-73. 2000. Lancaster, PA: Technomic Publishing.

Hewlett, J.D., and A.R. Hibbert (1967). Factors Affecting the Response of Small Watersheds to Precipitation in Humid Areas, Forest Hydrology, Pergamon Oxford, pp. 275-290

Konrad, C. P. & D. B. Booth, 2002. Hydrologic Trends Associated with Urban Development for Selected Streams in the Puget Sound Basin, Western Washington. USGS Water Resources Investigation Report 02-4040 with Washington Dept. of Ecology, Tacoma, Wash.

Kochanov, W. E., 1987. Sinkholes and Related Karst Features Map of Lehigh County, PA. PA Geologic Survey, Open File Report 8701, Harrisburg, PA

Kochanov, W. W., 1999. Sinkholes in Pennsylvania. PA Geological Survey, 4th Series, Educational Series 11, Harrisburg, PA

Linsley, et al., 1992. Water Resources Engineering, 4th Edition.

Madsen, R. and E. Figdor, December 2007, *When It Rains, It Pours: Global Warming and the Rising Frequency of Extreme Precipitation in the United States*.

Maryland Department of Economic and Employment Development (MDEED). 1989. *Economic Importance of the Chesapeake Bay.* MDEED, Baltimore, MD.

Maryland Department of the Environment, *2000. Maryland Stormwater Design Manual*.

Mas, D.M.L., Curtis, M.D., and E.V. Mas. 2001. "Investigation of Toxicity Relationships in Industrial Stormwater Discharges", presented at *New England Water Environment Association 2001 Annual Conference*, Boston, MA.

Massachusetts Department of Environmental Protection (MADEP) and the Massachusetts Office of Coastal Zone Management. 1997. *Stormwater Management, Volume Two: Stormwater Technical Handbook*. Boston, Massachusetts.

McCandless, T. L. and R. A. Everett, 2002. Maryland Stream Survey: Bankfull Discharge and Channel Characteristics of Streams in the Piedmont Hydrologic Region, US Fish & Wildlife Service, CBFO –S02-01, Annapolis, MD

McCandless, T. L., 2003. Maryland Stream Survey: Bankfull Discharge and Channel Characteristics of Streams in the Allegheny Plateau and the Valley and Ridge Hydrologic Regions, US Fish & Wildlife Service, CBFO-S01-01, Annapolis, MD

McCuen, Richard, 1979, Downstream Effects of Stormwater Management Basins, ASCE Journal of Hydraulics

McCuen, R. and Moglen, G., 1988, Multi-criterion Stormwater Management Methods, ASCE Journal of Hydraulics

Metropolitan Council. 2001. *Minnesota Urban Small Sites BMP Manual: Stormwater Best Management Practices for Cold Climates*, prepared by Barr Engineering Company, St. Paul, Minnesota.

National Marine Fisheries Service (NMFS). 2001. Statistics and Economics Division website URL: www.st.nmfs.gov/st1/index.html

National Research Council (NRC), (2008). Water and Science Technology Board, Division of Earth and Life Studies. "Chapter 3 Hydrologic, Geomorphic, and Biological Effects of Urbanization on Watersheds." *Urban Stormwater Management in the United States*. Washington, DC: National Academies Press, 109+. http://www.nap.edu/catalog.php?record_id=12465#toc

Natural Resources Defense Council (NRDC). 2006. *Rooftops to Rivers: Green Strategies for Controlling Stormwater and Combined Sewer Overflows.*

Natural Resources Defense Council (NRDC). 1999. *Stormwater Strategies: Community Responses to Runoff Pollution.*

New England Bioassay, Inc. 2001. *Final Report on Stormwater Toxicity Identification Evaluations (TIE) at Industrial Sites*. Prepared for the Connecticut Department of Environmental Protection.

New York State Department of Environmental Conservation (NYDEC). 2001. *New York State Stormwater Management Design Manual*. Prepared by Center for Watershed Protection, Albany, New York.

NOAA, 2001. Tropical Cyclones and Inland Flooding, US Dept. of Commerce, Natl. Weather Service, Bohemia, NY

Oberts, G. 2007, "Climate and Stormwater: Coping with Change," *Stormwater Magazine*, September 2007.

Oberts, G. 1994. "Influence of Snowmelt Dynamics on Stormwater Runoff Quality". *Watershed Protection Techniques*. Vol. 1, No. 2.

Ocean Co. SCD, 2001. Impact of Soil Disturbance During Construction on Bulk Density and Infiltration in Ocean County, NJ. Ocean County Soil Conservation District, Schnabel Engineering Assoc., USDA-NRCS. Toms River, NJ.

Owens, D. W., Jopke, P., Hall, D. W., Balousek, J., and A. Roa. 2000. *Soil Erosion from Two Small Construction Sites, Dane County, Wisconsin*. USGS Fact Sheet FS-109-00, U. S. Geological Survey

Pennsylvania Department of Conservation and Natural Resources (PADCNR), 2003. Geologic Shaded Relief Map of Pennsylvania, compiled by C. E. Miles, PA Dept. of Conservation and Natural Resources, Harrisburg, PA

Pennsylvania Department of Environmental Protection (PADEP), 2006, *Pennsylvania Stormwater Best Management Practices Manual*.

Pitt, Robert, 1985, 2002

Pitt, R., Field, R., Lalor, M., and M. Brown. 1995. "Urban Stormwater Toxic Pollutants: Assessment, Sources, and Treatability". *Water Environment Research*. Vol. 67, No. 3.

Prince George's County, Maryland. 1999. *Low-Impact Development Design Strategies: An Integrated Design Approach*. Prince George's County Department of Environmental Resources Programs and Planning Division.

Rabanal, F. and T. Grizzard. 1995. "Concentrations of Selected Constituents in Runoff from Impervious Surfaces in Four Urban Land Use Catchments of Different Land Use", *Proceedings of the 4th Biennial Stormwater Research Conference*, Clearwater, Florida.

Riley, A. L. 1985. *Riparian Restoration: A Timely New Mission for Federal Water Development Agencies.* Sacramento, CA: Department of Water Resources, Urban Streams Restoration Program.

Roberts, D. C., 1996. A Field Guide to the Geology of Eastern North America, Peterson Field Guide, Houghton Mifflin, New York

Sailer Environmental, Inc. 2000. *Final Report on the Alternative Stormwater Sampling for CMTA Members*. Prepared for Connecticut Marine Trades Association.

Sauer, L. J., 1998. The Once and Future Forest, Island Press, Washington, DC

Schueler, T.R. 1994. "The Importance of Imperviousness". *Watershed Protection Techniques*. Vol. 1, No. 3.

Schueler, T.R. 1995. *Site Planning for Urban Stream Protection*. Metropolitan Washington Council of Governments, Washington, D.C.

Schueler, T.R. 1999. "Microbes and Urban Watersheds". *Watershed Protection Techniques*, Vol. 3, No. 1.

Schueler, T.R., Kumble, P.A., and M.A. Heraty. 1992. *A Current Assessment of Urban Best Management Practices: Techniques for Reducing Non-Point Source Pollution in the Coastal Zone.* Department of Environmental Programs, Metropolitan Washington Council of Governments.

Scotese, C. R., 1997. Paleogeographic Atlas, PALEOMAP Progress Report 90-0497, Dept. of Geology, Univ. of Texas at Arlington, TX

Setia, P., and R. Magelby. 1988. "Measuring Physical and Economic Impacts of Controlling water Pollution in a Watershed." *Lake and Reservoir Management* 4(1): 63-71

Sorvig, K., 1993. Porous Paving. Landscape Architecture, Vol. 83, No. 2, Feb., 1993. Wash., DC

Shaver, E.J. and J.R. Maxted. 1996. "Technical Note 72 Habitat and Biological Monitoring Reveals Headwater Stream Impairment in Delaware's Piedmont". *Watershed Protection Techniques.* Vol. 2, No. 2.

Sloto, R. A., 1994. Geology, Hydrology and Groundwater Quality of Chester County, Pennsylvania, Chester Co. Water Resources Auth., w/USGS, West Chester, PA
Socolow, A. A., 1976. Pennsylvania Geology Summarized, Pa Dept. of Topographic and Geologic Survey, Ed. Series No. 4, Harrisburg, PA

Smullen, J. and K. Cave. 1998. "Updating the U.S. Nationwide Urban Runoff Quality Database". *3rd International Conference on Diffuse Pollution,* August 31 – September 4, 1998. Scottish Environmental Protection Agency, Edinburgh, Scotland.

Soil Conservation Service. 1975. *Urban Hydrology for Small Watersheds, USDA Soil Conservation Service Technical Release No. 55.* Washington, D.C.

Tobiason, S. 2001. "Trickle Down Effect". *Industrial Wastewater*. Water Environment Federation. Vol. 9, No. 6.

Troendle, C.A. (1985) Variable Source Area Models, Hydrologic Forecasting, M.G. Anderson and T.P. Burt (ed.) John Wiley, New York

United States Environmental Protection Agency (USEPA). 1983. *Results of the Nationwide Urban Runoff Program, Volume 1, Final Report.* Water Planning Division, Washington, D.C. NTIS No. PB 84-185 552.

United States Environmental Protection Agency (USEPA). 1990. *The Lake and Reservoir Restoration Guidance Manual, 2nd Ed.* EPA Doc. 440/4-90-006, USEPA, Washington, D.C.

United States Environmental Protection Agency (USEPA). 1997. *Urbanization and Streams: Studies of Hydrologic Impacts*

United States Environmental Protection Agency (USEPA). 1999. *Economic Analysis of the Final Phase II Storm Water Rule.* EPA Doc. 833-R-99-002, prepared by SAIC, Reston, VA.

United States Environmental Protection Agency (USEPA). 2000. *National Coastal Condition Report*. EPA841-R-00-001. Office of Water, Washington, D.C.

United States Environmental Protection Agency (USEPA). 2001. *National Water Quality Inventory: 1998 Report to Congress.* EPA620-R-01-005. Office of Water, Washington, D.C.

United States Environmental Protection Agency (USEPA), Office of Inspector General, 2007, *Development Growth Outpacing Progress in Watershed Efforts to Restore the Chesapeake Bay*, Report No. 2007-P-00031, September 10, 2007.

University of Illinois, *Weather World 2010 Project* internet site, (http://ww2010.atmos.uiuc.edu/(Gh)/home.rxml)

U.S. Water News Online, *Senate OKs Bill On Rural Water Adequacy*. 2007

Van de Verg, E., and L. Lent. 1994. *Measuring the Price Effects of Shoreline Erosion on Chesapeake Bay Area Properties Using the Hedonic Price Approach.* Toware a Sustainable Coastal Watershed: The Chesapeake Experiment. Proceedings of a Conference, 1-3 June 1994, *(Chesapeake Research Consortium Publication No. 149). Pp. 280-289.*

Viessman, W. and G. Lewis, 2003. Introduction to Hydrology, 5th Edition, Pearson Educ., Ltd., Upper Saddle River, New Jersey

Virginia Department of Conservation and Recreation (DCR) and the Center for Watershed Protection (CWP), 2001. *The Economic Benefits of Protecting Virginia's Streams, Lakes, and Wetlands*.

Virginia Department of Environmental Quality (DEQ), *Status of Virginia's Water Resources: A Report of Virginia's Water Supply Planning Activities 2003*, 2004
VA.

Virginia Department of Environmental Quality (DEQ), *Status of Virginia's Water Resources: A Report of Virginia's Water Supply Planning Activities 2004*, 2005
VA.

Virginia Department of Environmental Quality (DEQ), *Status of Virginia's Water Resources: A Report of Virginia's Water Supply Planning Activities 2005*, 2006
VA.

Virginia Secretary of Natural Resources (VASECNATRES), 2005, *Commonwealth of Virginia Chesapeake Bay Nutrient and Sediment Reduction Tributary Strategy*, January 2005

Water Environment Federation (WEF) and American Society of Civil Engineers (ASCE). 1998. *Urban Runoff Quality Management (WEF Manual of Practice No. 23 and ASCE Manual and Report on Engineering Practice No. 87).*

Watershed Management Institute, Inc. 1997. *Operation, Maintenance, and Management of Stormwater Management Systems.* In cooperation with U.S. Environmental Protection Agency, Office of Water, Washington, D.C.

Whitney, G. G., 1994. From Coastal Wilderness to Fruited Plain: A History of Environmental Change in Temperate North America from 1500 to the Present, Cambridge Univ. Press, New York

Winer, R. 2000. *National Pollutant Removal Database for Stormwater Treatment Practices, 2nd Edition.* Center for Watershed Protection, Ellicott City, Maryland.

Woodward-Clyde Consultants. 1990. *Urban targeting and BMP Selection: An Information and Guidance Manual for State NPS Program Staff Engineers and Managers, Final Report.*